UNIVERSITY OF ARIZONA
39001007038162

Digitized by the Internet Archive
in 2026

https://archive.org/details/ourmobileearth0000regi

OUR MOBILE EARTH

BROAD PEAK OF THE HIMALAYA.

OUR MOBILE EARTH

BY

REGINALD ALDWORTH DALY

STURGIS-HOOPER PROFESSOR OF GEOLOGY, HARVARD UNIVERSITY

ILLUSTRATED WITH MAPS, DIAGRAMS, AND PHOTOGRAPHS

"E pur si muove!"

CHARLES SCRIBNER'S SONS

NEW YORK · LONDON

1926

Copyright, 1926, by
CHARLES SCRIBNER'S SONS

Printed in the United States of America

UNIVERSITY OF ARIZONA
551.4
D15
LIBRARY

TO

LOUISE HASKELL DALY

COMRADE AND WISE COUNSELLOR
IN THE SEARCH FOR
THE MEANING OF THINGS

66243

AUTHOR'S NOTE

The illustrative material in this book, except in those cases where a special copyright or credit notice is printed beneath the particular illustration, is free for use for lantern slides, or for reproduction in other text-books, or in technical papers, or otherwise. It is the author's desire that these illustrations should be freely drawn upon, especially for purposes of education, and the copyright notice which covers the book itself is therefore not intended to cover the illustrative material.

In certain cases illustrations have been used in this book by special permission of the owners. Such illustrations are not subject to public use, and each of them is protected by special copyright.

CONTENTS

		PAGE
	INTRODUCTION	xix
CHAPTER		
I.	GREAT EARTHQUAKES OF HISTORY	1
II.	THE NATURE OF EARTHQUAKES	45
III.	THE EARTH'S INTERIOR	90
IV.	VOLCANIC ACTION	128
V.	CHANGES OF LEVEL. DISTORTION OF THE EARTH	170
VI.	MOUNTAIN RANGES	211
VII.	ORIGIN OF MOUNTAIN RANGES	251
VIII.	EVOLUTION OF THE FACE OF THE EARTH	292
	SUGGESTED WORKS OF REFERENCE	321
	INDEX	327

ILLUSTRATIONS

Broad Peak of the Himalaya . . . . . *Frontispiece*

FIG. PAGE

1. A street of Yokohama after the earthquake of 1923 2
2. Seismic map of the world 6
3. Map of the Tonga and Kermadec Deeps 7
4. Map of Japan and the Tuscarora Deep 9
5. Profile of the sea bottom between two of the Virgin Islands . 11
6. Seismic areas in Italy 12
7. Isoseismals of the Charleston earthquake, 1886 16
8. Epicenters and ocean deeps 17
9. Throw of a stone monument by the earthquake of 1897 in India 26
10. Torsion of a monument and of the ground during the 1897 earthquake in India 26
11. Memorial arch at Leland Stanford University after the earthquake of 1906 28
12. Flexure of a Messina pavement by the seismic waves of 1908 . 29
13. Telescoping of a 30-inch water pipe by the California earthquake of 1906 31
14. Tensional rupture of a 30-inch water pipe by the California earthquake of 1906 31
15. Landslide at Cape Fortunas caused by the California earthquake of 1906 33
16. Rock débris ejected by seismic fountains, and accompanying craterlets; California earthquake of 1906 35
17. Diagrammatic section illustrating the origin of sand dikes and seismic craterlets 36
18. A group of sandstone dikes of seismic origin; Shasta County, California 37
19. Pond formed by seismic deleveling along the San Andreas Rift, California 39
20. Map of some of the main faults of California, showing the relation of three cities to those faults 42

FIG.		PAGE
21.	Tensional stress in a bent slab and its ultimate fracture	47
22.	Modes of faulting	48
23.	Fault scarp formed during the Japanese earthquake of October 28, 1891	48
24.	Map of seismically active faults in the vicinity of San Francisco	49
25.	Fault scarp caused by the 1906 displacements along the San Andreas Rift	51
26.	Group of earthquake cracks forming a belt along the San Andreas Rift	51
27.	The San Andreas Rift near its northern end	53
28.	Fault scarp in the San Andreas Rift; Mojave Desert	54
29.	Offset in 30-inch water pipe by the 1906 fault at the San Andreas Rift	55
30.	Offset of fence by the 1906 Californian earthquake	55
31.	Twenty-foot offset of road by the 1906 Californian earthquake	57
32.	Displacement at the Neo Valley Rift, Japan	58
33.	Isoseismal lines of the California earthquake of 1906	59
34.	Areas of sensible shock in various Chilian earthquakes	61
35.	Displacement of farm boundaries along the Japanese rift of 1891	63
36.	Sudden uplift of the Alaskan coast during the earthquake of 1899	66
37.	Map of part of the Alaskan coast, showing different amounts of uplift, connected with the earthquake of 1899	67
38.	Map of lines of equal subsidence connected with the Messina earthquake of 1908	68
39.	Partial drowning of a village on a coastal plain of New Guinea by seismic subsidence	69
40.	Map of Sagami Bay, showing amounts of deleveling of the sea bottom, connected with the Tokyo earthquake of September 1, 1923	70
41.	Rock bench and sea cliff, uplifted during the Tokyo earthquake of September 1, 1923	72
42.	San Jacinto fault scarp at upper end of Borego Valley, California	73
43.	Migration of earthquake centers in Italy	77
44.	Seismic map of Japan, showing locations of its principal volcanoes	78

FIG. PAGE

45. Diagrammatic representation of the relations of seismic focus, epicenter, wave fronts, wave paths, and isoseismals . . . 80
46. Wave paths and their refraction at the surface of the solid rock . 83
47. Spreading of the sound of the Hereford earthquake 84
48. Diagram of the motion of particles during the passage of longitudinal and transverse waves 85
49. Seismogram of a 1909 earthquake, registered at Pulkovo, Russia 86
50. Section through the center of the earth, showing the paths of earthquake waves, their refractions and reflections, and some of their times of arrival at points on the earth's surface . . 87
51. Canyon cut in old granite by the Orange River, South Africa . 93
52. Hurricane fault scarp, Utah 94
53. Flat-lying strata, south of Wick, Scotland 96
54. Banded gneiss of the oldest series of rocks in Scotland . . . 97
55. Basaltic flow on the floor of the Kilauea sink, Hawaii . . . 98
56. Diagrammatic section showing distribution of densities in and below the earth's crust 100
57. Diagrammatic section illustrating a mountain "root" . . . 102
58. Diagram illustrating the ellipticity of the earth 103
59. Diagrams illustrating a lithospor and a ferrospor 107
60. Section through the earth's center, showing the iron core, the layer of transition, and the silicate shell, with densities . . 108
61. Escarpment of the basaltic plateau of Basutoland, South Africa 117
62. Superposed flows of basaltic lava, Island of Saint Helena . . 119
63. View of the crust on the liquid lake of lava at Kilauea, Hawaii . 120
64. The deeply eroded, basaltic island of Tutuila, American Samoa 121
65. Section illustrating the sudden change in the rocky material at the depth of 50–60 kilometers below the earth's surface . . . 123
66. Liquid basalt flowing over a sea cliff in Hawaii 125
67. Mount Ararat 129
68. Mayon volcano of southern Luzon, Philippines 130
69. A young lava flow from a long fissure, Ascension Island . . . 131
70. Eruption of a geyser, Yellowstone National Park 132
71. Diagrammatic cross-section of the Yellowstone Park plateau . 133

FIG.		PAGE
72.	Cross-section of a basaltic flow at Williams Canyon, Arizona	134
73.	Location of the Deccan plateau of India	135
74.	A vesicular basalt from Hawaii	136
75.	A vertical dike of basalt, Island of Arran	138
76.	An eroded dike, Spanish Peaks district of Colorado	139
77.	Map of some feeders of the fissure eruptions in Washington State	140
78.	Vents of the central type, developed along a fissure on Mount Etna	141
79.	Chains of volcanic cones in Java	142
80.	Trend lines of the volcanic islands in the Pacific	143
81.	Cross-section of a magma chamber in the crust	145
82.	Longitudinal section of the magma chamber of Figure 81	146
83.	Cross-section of the top of a dormant volcanic cone	148
84.	The cone of Fujiyama, Japan	149
85.	Photograph of a model of the Kilauea sink	150
86.	Kilauea (Halemaumau) lava lake with a built-up rim	151
87.	Diagrammatic cross-section of the lava lake at Kilauea in the year 1909	152
88.	Fountains of molten rock at Kilauea in the year 1912	153
89.	An explosion at Kilauea in May, 1924	154
90.	Ejected blocks of rock forming part of an ancient volcanic cone	155
91.	Typical basaltic cinder cone, near Mono Lake, California	156
92.	Map and section of the volcanic cone of Bandai-San, Japan	157
93.	Cross-section and plan of a basaltic neck	158
94.	"Lot," a monolithic volcanic neck, Saint Helena Island	159
95.	Diagram showing intrusive sheets or sills of igneous rock	160
96.	Mount Gould, Lewis Range, Montana Rockies	161
97.	Cross-section of Burnett Creek laccolith, Montana	162
98.	Unsymmetrical laccolith at Black Butte, Montana, seen in cross-section	162
99.	Map of part of Swabia, showing positions of volcanic vents	163

FIG. PAGE

100. Model of the Island of Hawaii 164

101. Diagrammatic cross-section through Mauna Loa and Kilauea . 165

102. View of extruded domes of highly viscous, trachytic lava in Ascension Island 166

103. Extruded dome of trachyte, Island of Saint Helena 167

104. Shallow seas transgressing North America at an epoch of the Eocene period 172

105. Shallow seas transgressing North America at an epoch of the Cretaceous period 172

106. Shallow seas transgressing North America at an epoch of the Mississippian period 173

107. Shallow seas transgressing North America during Lower Cambrian time 173

108. Wave-cut rock bench of Aunuu Island, American Samoa . . 175

109. Wave-cut rock bench of Tau Island, American Samoa . . . 176

110. Wave-cut rock bench at Jamestown, Island of Saint Helena . 177

111. Cave cut by the ocean waves in granite at the Cape of Good Hope 178

112. Bench cut by the ocean waves in sandstone at the Cape of Good Hope 179

113. Map showing the distribution of the principal ice-caps of the Glacial period 181

114. The composite ice-cap of North America at the maximum of glaciation 183

115. Cross-section of a typical living coral reef and the platform on which it rests 184

116. Map and cross-section of the Funafuti atoll, South Pacific . . 185

117. Contemporary warping of Scandinavia 186

118. Extent of the last ice-cap in northwestern Europe, and the directions of the flow of its ice 188

119. Extent of the "Yoldia" sea 189

120. Diagrammatic cross-sections illustrating how the earth's crust has been basined by a glacial load 191

121. Boulders dropped on rock ledges of Labrador as the Labrador ice-cap melted 192

122. Bear Island, off mainland of eastern Labrador 193

FIG.		PAGE
123.	Raised boulder beach near Sloop Harbor, Labrador	194
124.	Map showing the post-Glacial warping of Newfoundland	195
125.	Boulder beach on the Island of Hogland, Gulf of Finland	196
126.	Rock bench cut by the ocean waves, Island of Luing, Argyllshire	197
127.	Sea cave in cliff at edge of the 25-foot raised beach; west coast of Island of Jura, Argyllshire	198
128.	One-hundred-foot raised beach at top of sea cliff; west coast of Island of Jura	199
129.	Cross-sections illustrating the deformations of the ground, connected with glaciation	200
130.	Map of geosynclines in North America	202
131.	Ripple-marks on sandstone beds at the summit of the Selkirk Mountains	204
132.	Cross-sections illustrating the weakening of the earth's crust by the formation of a geosynclinal	205
133.	Europe at an epoch of the Cretaceous period	207
134.	Axial trends of the Alpine and related ranges of mountains in Europe	213
135.	Map showing locations of the chief high, young, and rugged chains of mountains	215
136.	Map suggesting the prolongation of the structure of the Andes into West Antarctica	217
137.	Thin-bedded flagstones of Holborn Head, Caithness	220
138.	Upturned beds of sandstone and shale at Gamka Poort, Cape Province, South Africa	221
139.	Anticline in stratified rocks of England	222
140.	Mount Heavens, Montana	223
141.	Crumpling of limestone beds, Banffshire	224
142.	Experiments imitating the folds found in mountain ranges	225
143.	Experiment imitating the thrusts found in mountain ranges	226
144.	Cross-section and perspective view of an eroded syncline	227
145.	Cross-section and perspective view of an eroded anticline	227
146.	Diagram of the structure and relief of the Jura Mountains	228
147.	Map and section of part of the Jura range	229

FIG.		PAGE
148.	Overthrust mass of Chief Mountain, Montana	230
149.	Lewisian gneiss thrust over much younger (Cambrian) sandstone	231
150.	Bared sole or surface of thrust	232
151.	Cross-sections illustrating typical Alpine structures	233
152.	Map of mountain trends in Asia	236
153.	World-map, showing positions of the shields and of the two major zones of down-warping	243
154.	Inner gorge of the Colorado Canyon, Arizona	245
155.	Cliff at Cape Mugford, Labrador	246
156.	Map showing outcrops of pre-Cambrian rocks in North America	247
157.	Plain of marine erosion on folded Carboniferous strata, near Weaklaw, Scotland	252
158.	Flexure of the crust and mountain-making in the Transvaal	253
159.	Ridge of quartzitic sandstone, Bushveld, near Pretoria; south side of eruptive complex	255
160.	Ridge of quartzitic sandstone, Bushveld; east side of eruptive complex	257
161.	Ridges of quartzitic sandstone, Bushveld; north side of eruptive complex	257
162.	The Sierra Nevada seen from Mono Lake	259
163.	Wegener's maps illustrating his idea of continental migration	261
164.	Section illustrating the furrowing of the earth's surface	264
165.	Sections illustrating the development of stresses by the doming of the earth's crust on a continental scale	267
166.	Diagrams illustrating the crumpling of geosynclinal rocks by the sliding of a large block of the earth's crust	269
167.	Section of a lava-flow in Ascension Island; analogy with continental displacements	272
168.	Diagrams illustrating the chief cause of mountain height	276
169.	Atlantic type of coast-line	281
170.	Pacific type of coast-line	283
171.	Glacial till of Carboniferous age (Dwyka), South Africa	285
172.	Glacially striated pavement of rock, north of Kimberley, South Africa	286

FIG. PAGE

173. Taylor's world-map, showing his conception of the migration of continents and associated mountain-building 288

174. Sea cliff near Monterey, California 293

175. Connecticut of late Paleozoic time 294

176. Connecticut at the beginning of Triassic time 294

177. Connecticut when the Triassic basin was completed . . . 294

178. Block mountains of Connecticut in early Jurassic time . . . 296

179. Connecticut in the Cretaceous period 296

180. Connecticut at the close of Tertiary time 296

181. Connecticut in the Glacial period 298

182. Connecticut at present 298

183. Tidal distortion of the earth 300

184. Instability of the sun, resulting from a "slow" encounter with another star; according to Jeans 302

185. The solar filament, the original form of the planetary system; according to Jeans 302

186. Wegener's world-map, showing the outlines of the continental masses 312

187. View in the Karakorum Himalaya 319

INTRODUCTION

In its response to external forces the earth acts as if it were very much alive. Ceaselessly the sun pours its radiant energy. Hence, winds are always blowing; rivers are always flowing; sea waves are always touring the oceans and pounding the continents; glaciers, also children of the sun, keep steadily ploughing out the rocks. The mobility, the liveliness, of air or ocean is familiar to us. Less obvious is the real mobility of the earth's rocky body. This phase of the earth's "aliveness" is the subject of the present book.

Forces from without and forces from within, or body forces, have made and are making mighty changes in the shape and constitution of our solid globe. These changes have been as complex as the interplay of the many forces. Yet there has been system in the earth movements. Some are rapid, terrifyingly rapid: the earthquakes. Other, slower movements have altered the relief and composition of the earth's crust: volcanic events. Some of the changes have been brought about in calm, dignified leisure, but their results are revolutionary: widely spread uplifts and sinkings of the crust. Equally irresistible forces have thrown the earth into spasms, long drawn out: belts of the crust have been crumpled to form the mountain ranges.

The following pages thus have as their topic the earth's mobility as expressed in earthquakes, in volcanic action, in broad warpings of the crust, and in the paroxysms of mountain-building. Since all of these movements have depended on the nature of the earth's interior, we must dwell on that fundamental subject. Finally, we shall consider the special mobility of the globe during its infancy. Like other infants, it was then most restless, most plastic, most ready to respond to forces. Then its character was made. Then the principal conditions for the activities of an aging earth were established.

Even those who are familiar with the facts, the principles, and the many residual mysteries of geology realize at once the difficulty of tracing the evolution of the earth's rocky figure. The trained geologist knows full well the impossibility of telling the story in full detail. Yet there is need for an occasional review of those discoveries and conclusions which appear to be consistent among themselves and to indicate the broad outlines of our globe's development. The statements of facts and hypotheses come from the scientific press in a bewildering flood. So that geologists may not drown in it intellectually, they must attempt synthesis. They must try to discover general formulas which will summarize, describe with increasing universality, their myriads of ascertained facts. There is but one way to do this—by the method of trying all conceivable formulas, to see which are the best to fit the facts.

An example is found in the old, outstanding question whether the earth was molten at its surface after it had attained practically its present mass. Expert students have answered that question in the affirmative; others, in the negative. It is obvious to the geologist at least that the whole physical history of the globe, in theory, could not fail to follow different lines according to the two views about the young earth. If, as once more to be suggested, the young, full-bodied earth was molten and therefore specially mobile at the surface, then a whole chain of inevitable consequences should be found to be matched by the accessible facts of geology. If the alternative hypothesis of initial solidity at the surface were correct, it would necessarily control interpretation of the same multitude of facts.

Inasmuch as cosmogony and geology are both young sciences, consensus of opinion about the earth's origin and history is still reserved for the future. Meantime these sciences are advancing through the erection and testing of competing hypotheses; in other words, through speculation, controlled by all the available facts. Science progresses through systematic guessing in the good sense of the word.

This book attempts to sketch leading processes by which the

earth has attained its present shape and structure. The description includes steps that are agreed upon by working geologists, and also elements in more or less lively debate. Unfortunately, some of the disputed doctrines are among the most fundamental. They can be phrased only speculatively. It is inevitable that an author should stress those essential speculations which appeal to him as the soundest. This is done in the following chapters, whose purpose forbade adequate discussion of all alternative hypotheses. The book contains the substance of a course of public lectures, given during January, 1925, at the Lowell Institute of Boston. It is published, in spite of the necessarily condensed, rather bald and dogmatic form of statement incidental to addresses before a popular audience.

The general reader will doubtless be somewhat troubled by the technical names and phrases sprinkled through these pages. He is begged to remember that the subject is one which can hardly be treated at all without the entrance of some technicalities. My scientific colleagues, on their part, will here miss satisfactory discussion of principal points of the general argument. In part, such lacking elements are treated elsewhere, in the professional literature; for the rest, it is hoped that their future, fuller discussion may be possible. Perhaps the working geologist will find some features of interest in a book, boldly planned on an endlessly difficult theme, but intended for the general reader.

For help in preparing the material of this book my debt to men of science and their publishers is great. The amount of their assistance is but faintly indicated by the bibliography and by the many references to sources in the legends of the illustrations. To all the authors most hearty thanks are due, not only for the stimulus of their writings but also for their permission to reproduce illustrations in their published works. Similar courteous permission has been granted by the publishing houses of D. Appleton and Company, G. Borntraeger, The Cambridge University Press, The Carnegie Institution of Washington, Armand Colin, E. P. Dutton and Company, G. Fischer, Ginn and Company, Henry Holt and Company, The Macmillan Com-

pany, Macmillan and Company, Masson et Compagnie, The McGraw-Hill Book Company, E. Naegele, The University of Chicago Press, and The D. Van Nostrand Company. A number of photographs were kindly supplied by the directors of the Geological Surveys of Scotland and the United States and by the Commissioner of Boundary Surveys, Canada. The Gardner Collection of Photographs at Harvard University furnished other useful illustrations. Photographs from W. T. Grenfell, K. Maehara (Camera Craft Shop, Hilo, Hawaii), Y. Oinouye, N. Yamasaki, and F. E. Wright have also been of value in portraying the facts of nature.

For suggesting and aiding the preparation of the lecture material, which has been amplified and partly rewritten for presentation in book form, my appreciative thanks are due to President Lowell, Trustee of the Lowell Institute of Boston.

Special acknowledgment is due to my wife, Louise Haskell Daly, who throughout the writing acted as amanuensis and as able, constructive critic of thought and language.

OUR MOBILE EARTH

OUR MOBILE EARTH

CHAPTER I

GREAT EARTHQUAKES OF HISTORY

In 1905 the present director of the Seismological Institute of Japan pointed out the grave danger to Tokyo through the breaking down of its system of water supply by an earthquake. He wrote: "We might experience a loss of lives to the extent of 100,000 or more." Then and later his opinion was ridiculed "as nothing other than a rumor which might cause a general panic."

Seventy-six seconds before noon on September 1, 1923, the tragic fulfilment of his forecast began as a trembling of Tokyo ground. The shaking reached its maximum in about sixteen seconds, but continued the wreckage of this city of 2,000,000 inhabitants for nearly five minutes. Ten to twenty times as much destruction was wrought by the innumerable fires which sprang up all over the city and spread under a typhoon gale. Though on a greater scale, the catastrophe repeated that of San Francisco in 1906. In each case the water system broke down.

Yokohama, with half a million inhabitants, was ruined even more thoroughly during the same minutes of 1923 (Figure 1).

According to official figures (probably underestimates throughout), 99,331 persons were killed in the district including Tokyo and Yokohama; 43,476 persons were missing; 103,733 persons were wounded. The houses destroyed numbered 576,262. The property loss has been estimated at $4,500,000,000. It is said that 32,000 persons were burned to death in the Military Clothing Yard at Tokyo. Many more perished in pools of water that boiled with the heat of the conflagration.

The supplies of food, water, fuel, and clothing, and means of transportation for several millions of people suddenly vanished. Can any one estimate the subsequent vital, social. and material

FIG. 1. A STREET OF YOKOHAMA AFTER THE EARTHQUAKE OF 1923.

losses that host has suffered because of the cataclysm, and will continue to feel for many years to come?

Only recently has damage from earthquakes been properly recorded, and then only in civilized lands. Yet the sample figures given in Table I are sufficiently impressive.

When Lisbon lost its 60,000 lives, Europe received the greatest shock ever scientifically recorded for that continent. Owing to special conditions, the incomparably less energetic earthquake at Messina, 1908, was more destructive, and holds the European record for number of fatalities. The adjacent Calabria, the toe of Italy, has seen disaster several times, and is one of the most uneasy parts of the European continent. The Messina and

Table I

CASUALTIES OF INDIVIDUAL EARTHQUAKES

REGION; DATE	PERSONS KILLED	PERSONS WOUNDED
Lisbon, 1755	60,000	....
Calabria, 1783	30,000	....
Naples, 1857	12,300	1,400+
Argentina, 1861	6,000	....
Andalusia, 1884	750	1,500+
Charleston, 1886	27	....
Riviera, 1887	640	600
Japan, 1891	9,960	20,000
Calabria, 1894	100	960
Japan, 1896	29,000	5,000
India, 1905	20,000	....
California, 1906	500	....
Valparaiso, 1906	3,764	....
Calabria, 1907	175	50+
Jamaica, 1907	1,000+	....
Messina, 1908	100,000+	....
Central Italy, 1915	30,000	....
Kansu, China, 1920	100,000–200,000	....
Japan, 1923	142,000+	103,700+

Kansu catastrophes were the worst of our times up to 1923. The Japanese losses of 1891 and 1896 are still fresh in many minds.

Chinese records of seismic damage reach back more than 1,000 years. They are not accurate, but, in spite of probable exaggeration, Table II illustrates the kind of scourging which China has suffered during the last 900 years.

Table II

REPORTED LOSS OF LIFE, CHINESE EARTHQUAKES

YEAR	PERSONS KILLED	YEAR	PERSONS KILLED
1038	22,000	1730	100,000
1057	20,000+	1834	8,000
1290	100,000	1850	15,000+
1556	830,000	1920	100,000++
1622	20,000		
1662	300,000		1,515,000

Big with meaning as they are, these tables are but pale examples of records from a few centuries. Many more catastrophes were enacted before losses were measured and written down.

Mallet, the father of the science of earthquakes, estimated the lives lost through earthquakes during 4,000 years to have numbered 13,000,000. Nevertheless, the fame of seismic disasters is not due to the total damage occasioned by earthquakes. In part men are impressed specially because the human tragedies are concentrated in space and time. Of at least equal influence is the periodically renewed, nerve-racking discovery that the solid earth, the very symbol of stability and reliability, has treacherously failed. The horror of the earthquake is largely a matter of the imagination, often quickened to the breaking point of sanity. Hence, for more than one reason, man tends to exaggerate the relative damage done by earthquakes to himself and his works. As a corrective one does well to view that damage in relation to other scourges. We glance at the newest pestilence, the automobile. Mallet's estimated rate of killing for the whole earth during forty centuries is only one-sixth of the rate at which the automobile is destroying lives in the United States alone. When, in addition, we think of the infinite load of fear which the automobile has brought upon the responsible members of the American public, we see at once that there is no particular reason why we should become hysterical over earthquakes.

It is a question whether this chronic fear of the automobile, this imponderable damage to the happiness and health of the inhabitants of our country, is not a greater loss to our civilization than all the killings and maimings on our highways. Similarly, no statistician can declare the packed misery of the fateful minutes of an earthquake, nor the prolonged agony of personal and social reconstruction. He must fail to tell the story, just as art must fail. No Æschylus or Dante can reach the heart of such a matter. It is as unimaginable as the drowning of a million men, women, and children in a single flood of the Yellow River; as ungraspable as the Great War. However, the little part of the sorrow which the outside world can imagine, prompts almost unexampled sympathy, compassion, and remedial measures.

Men need not be content with remedial measures. Though seismology, the science of earthquakes, is very young, we already

know much concerning the nature of these movements and concerning the regions where they are important. Knowledge of their nature will help engineers and other men of business to build more stable houses, towns, railways, water-supply systems, and docks. Knowledge of distribution, especially with respect to the kinds of rock formations in the ground, will guide city fathers and statesmen in planning town sites, port facilities, and railway lines. The problem of forecasting earthquakes is intrinsically difficult, but some suggestions are in hand for at least a partial solution.

Not only has this new science practical bearing on human welfare; seismology has already thrown a flood of light on the nature of the earth's deep interior. That mysterious, hidden part of the planetary body dominates many of the processes that have made the surface of the globe what it is. Earthquakes traveling through the interior of the globe are like so many messengers sent out to explore a new land. The messages are constantly coming and seismologists are fast learning to read them.

Summaries of seismological progress are being made in special text-books of increasing excellence. However, there is need for less technical reviews of the subject. This chapter begins such a sketch or briefest outline, and is chiefly confined to the effects of earthquakes. By their fruits we may know earthquakes. Our study deals with numbers, quantities, measurements, for these form the essence of the truth of nature. Yet the figures can not be dry, since they so often quicken our imaginations and tap wells of sympathy for millions of our fellows.

The conditions for the loss of life and property in shaken regions will be noted. On this mental thread may be strung leading facts of the physical science, while the human drama is always kept in the foreground, where it belongs. On occasion some seismic effects, that are not so vital to mankind, but yet have geological significance, will be noticed.

First, the luck of locality. Every intelligent person knows that seismicity, or the tendency to earthquakes, is not evenly distrib-

uted over the earth. Through their long histories London and Paris have felt but few shocks; Constantinople and Peking have felt many strong shocks. But only recently has it become clear that the separation of strongly seismic and more stable areas of the earth's surface is tolerably systematic and comparatively

FIG. 2. SEISMIC MAP OF THE WORLD. (After Reeds.)

easy to describe. Seismicity tends to be both chronic and acute in two belts running round the earth. See Figure 2.

The one belt is along the border of the Pacific Ocean basin. The other follows the zone of the mediterranean seas and the associated, roughly east-west system of mountains, from the East Indies, through Himalaya, Alps, Pyrenees, West Indies, to Central America, where it again cuts the circum-Pacific belt. In these two belts the shaking of the ground is both more persistent and, as a rule, more energetic than elsewhere; there the seismic cataclysms have been largely concentrated throughout human history. The cause of the actual degree of concentration

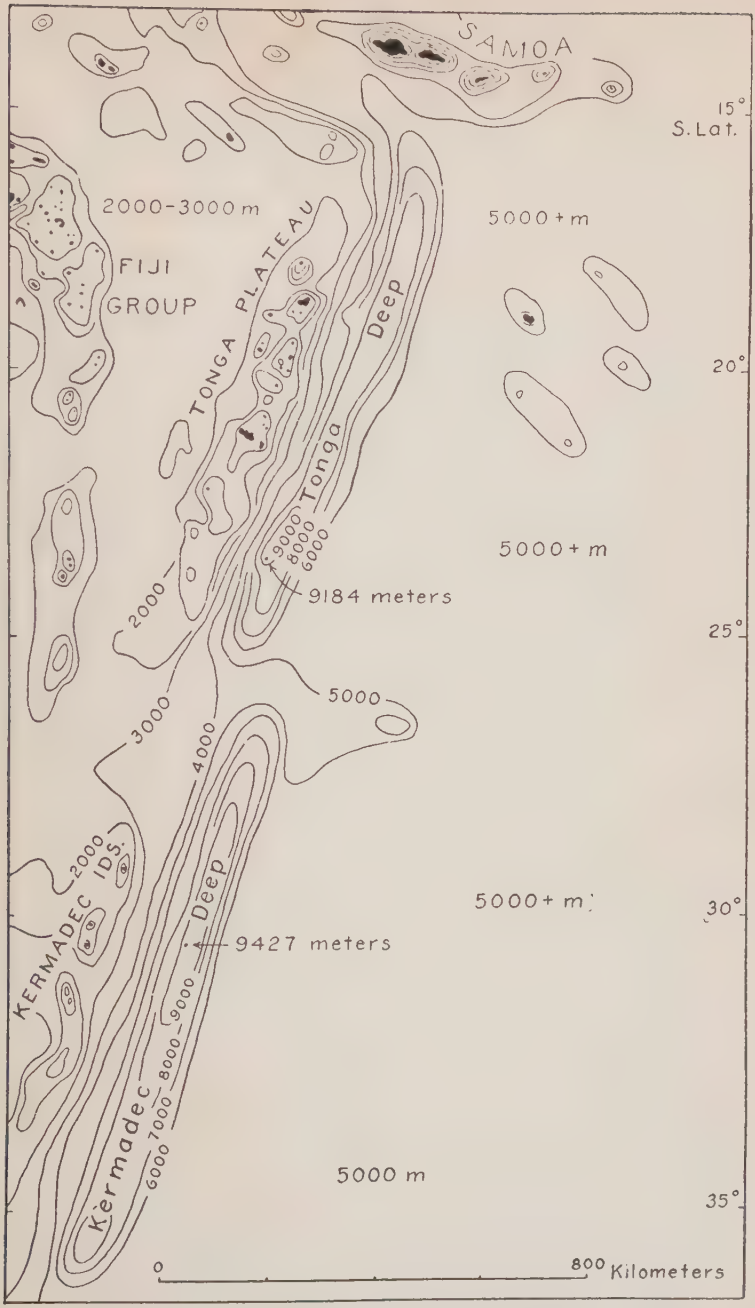


FIG. 3. MAP OF THE TONGA AND KERMADEC DEEPS.
Isobaths show depths in thousands of meters.

in the two belts will be noted in the seventh and eighth chapters, where seismicity is seen to be a necessary consequence of strains that were set up when the earth's young, high, and rugged mountains were built. The two seismic zones are thus practically coincident with the world's two mountainous zones, the mountains of which were formed in recent time, geologically speaking.

On the map, Figure 2, the seismic belts are stippled. The larger dots represent the centers of the 276 major earthquakes, those which affected the seismographs all over the globe, during the period from 1899 to 1911, inclusive. Within the same time 679 additional earthquakes were recorded, whose waves reached only part of the way round the earth in each case. Their points of origin are not shown on the map, but they had a distribution essentially similar to that of the major earthquakes.

FIG. 4. MAP OF JAPAN AND THE TUSCARORA DEEP. (After Omori.)

A considerable number of the major shocks centered in the western Pacific region, far from land, and thus outside the mountainous zones. This exception to the rule seems to find explanation in the fact that the earth's crust under the western Pacific is strongly warped, out of level, strained. In part at least, this

condition of strain is connected with the building of the mountains of eastern Asia and Australasia.

Specially disturbed is a large area of the southwest Pacific, including the Tonga and Kermadec Islands and the submarine Tonga Plateau. Tremendous shocks originate at the foot of the plateau on its eastern side, where the sea bottom drops to form the Tonga Deep, which is one of the profoundest troughs of the ocean floor. Figure 3 shows this topographic relation, and also the positions of the volcanic islands of Samoa and Eastern Fiji, indicated in black. The Kermadec Deep lies *en axe* with the Tonga Deep, and is comparable with it in length, width, and depth. Depths are given in meters. The contour lines ("isobaths") of the sea bottom represent vertical differences of level in thousands of meters. The maximum depths yet found in the two deeps are indicated; each maximum is approximately six statute miles. It seems clear that these two important deeps were formed when the young mountains to the west were built. Of those the main islands of Fiji are the emerged tops, but for the most part the mountain structures of the western Pacific are submarine.

Similarly, Japan drops off into the famous Tuscarora Deep, which has a maximum measured depth of 4,655 fathoms, or 28,000 feet, or 8,500 meters. The total descent of the rock surface is about six miles, or nearly ten kilometers. Figure 4 shows, in solid black, Japan and part of the mainland of Asia; contour lines of the sea bottom or isobaths in thousands of meters; part of the Tuscarora Deep; and the numbers and locations of severe earthquakes which were felt by Japan within the twenty-year period from 1885 to 1905. Of the total number more than half of the shocks originated on the steep western slope of the Tuscarora Deep.

If the Japanese rocks were suddenly liquefied, they would flow down and level up the Tuscarora Deep. The tendency to do that is resisted only by the elastic strength of the rocks. The pressures are there, constant, at this moment. There the earth's crust is in a persistent state of stress. At intervals the strained

crust snaps and moves a little. Each snapping means an earthquake. The extraordinary departure of the crust from level is thus connected with Japan's unfortunate record; with Tonga it holds the world's record for seismicity. Just as in the case of

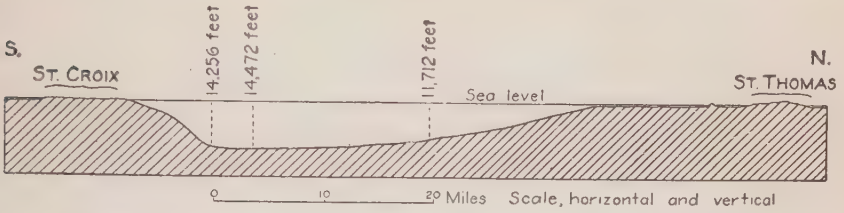


FIG. 5. PROFILE OF THE SEA BOTTOM BETWEEN TWO OF THE VIRGIN ISLANDS.

Tonga, Japan's chief source of danger lies beneath the sea, whence have come forty-seven of the very heaviest shocks written into Japanese history.

The West Indian region of the Virgin Islands furnishes another example of strong earth-shaking at oceanic deeps. The section of Figure 5 runs between the islands of Saint Croix and Saint Thomas. The scale is natural; that is, there is no exaggeration of the vertical. Depths are shown in feet. They are much smaller than those found in the Pacific deeps just described; nevertheless, the crust supporting the Virgin Islands is clearly stressed. It is snapping periodically; during the years 1867–8 the islands were shaken with special severity.

Seismic danger to the coast of Chili and Peru almost rivals that to Japan. The submarine slope of the Andes is about as steep as the slope of the sea bottom off Japan, and on the average is from three to ten times steeper than the continental slopes off eastern America, off Australia, and off western Europe—all comparatively free from earthquakes.

In each of these cases steepness of the topography is probably not the sole cause for the local instability of the earth's crust. Certain observations tend to show that a vertical column of the crust under each deep trough weighs less than a vertical column of similar cross-section within the adjacent plateau or

mountain chain. Such a defect of matter under the trough, coupled with excess of matter under the surface of the plateau, means that there are unbalanced pressures at the bottom of the crust. The crust under the trough is being pressed up; the crust under the plateau tends to sink vertically. Clearly, the crust be-

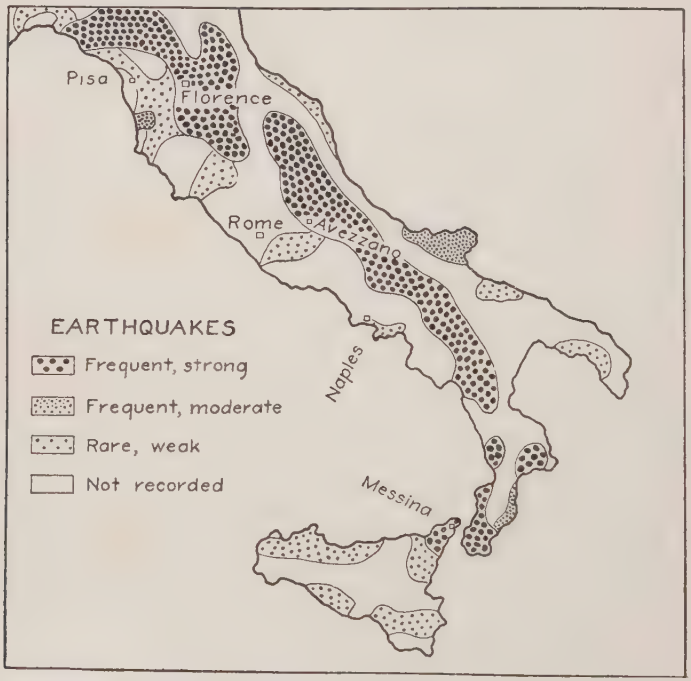


FIG. 6. SEISMIC AREAS IN ITALY. (After Sieberg in "Erdbebenkunde," G. Fischer, Jena.)

tween the bottom of the trough and the top of the plateau must be charged with vertical shearing stresses, and that through the whole thickness of the crust. Intermittent, sudden yielding of the thick, rocky mass causes the succession of earthquakes. In the future, when these adjustments have equalized the pressure under the crust of the whole region, through flow of the material under the crust, this cause of earth-shaking shall have been removed. How the crust came to be strained in this way originally is a problem for a later chapter.

The earth's crust is stressed for reasons other than steep topog-

raphy and unequal pressures under the crust. Those reasons are not obvious, nor is it clear why the stressing is so unequally distributed. These questions arise when one studies the two major earthquake belts themselves. For example, the leg bones, and especially the toe, of Italy are often severely shaken, while the shocks administered to the shin, calf, and heel tend to be relatively feeble. See Figure 6. Hence the luck of locality is with Ravenna, Rome, the Leaning Tower of Pisa, and even with Naples, within sight of Vesuvius. Venice appears to be outside the zone of maximum danger. Its architectural jewels have escaped seismic damage, perhaps also because Venice is founded on *deep* alluvium, a substance which tends to dampen down vibrations of the ground with special rapidity. This is true, though, as we shall see later, foundation on *shallow* alluvium or on "made ground" gives the worst possible condition for the safety of a city from earthquakes. Florence has often been shaken, but, since its history began, never with the relentless power that annihilated Reggio and Scilla (Scylla) in 1908. For the landsmen of Scylla and Charybdis have found new truth in Homer's submarine monster of Messina Straits.

In most places where the seismic disease is acute, it is also chronic. Long before modern instruments for the registration of earthquakes were invented, the Japanese were keeping record of quakes sensible to man. The first clearly noted was in 416, A. D. Between that year and 1867, the number recorded was more than 2,000, of which 223 were classed as destructive. During the same centuries Kyoto, the capital of Japan for 1,100 years, was shaken 1,318 times; "destructively," 34 times; "strongly," 194 times. The heaviest shock of Japanese history took place on October 28, 1707.

With the advent of the wonderfully sensitive seismograph the uneasiness of Japan became much more evident. Thus, between 1885 and 1903, records of 27,485 earthquakes were there made: an average of 1,447 per year, or 4 per day.

The 1923 earthquake, the most fatal of all, was really not comparable in intensity with many others; it belonged to the

second or third category of shocks, classified on the basis of energy displayed. The destruction of Tokyo and Yokohama was largely due to their unfortunate location on shallow beds of weak alluvial material, which took up the vibrations from the stronger rocks beneath, and then shook like a stiff jelly. The blow was, of course, heavier at points which were nearer to the center of disturbance, under Sagami Bay. Hence the city of Kamakura suffered severely. However, in passing we may note that, though its colossal bronze statue of Buddha was displaced, that placid face remains as before, a symbol of the marvelous self-control of the Japanese people, who have been trained through the centuries in the school of danger.

Within a period of 30 years, Italy has felt 13,500 earthquakes, including the after-shocks of major disturbances, or at the average rate of 450 shocks each year.

For the whole earth the average number of shocks registered by seismographs is 9,000 per year, or about one every hour. Of the annual average, 5,000 are strong enough to be felt, and 107 are strong enough to damage buildings. A world-shaking of the first rank occurs, on the average, every 18 days. Fortunately, most of these originate under the ocean and do comparatively little damage.

Though no part of the earth is indefinitely free from earthquakes, these are both weak and rare outside of the two great-circle zones. Our own New England is typical.

Between 1620 and 1869 this part of the world was shaken 231 times. Bradford's "History" gives a quaint description of the first earthquake recorded after the landing at Plymouth Rock: "This year [1638] aboute y^e^ 1. or 2. of June was a great and fearfull earthquake; it was in this place heard before it was felte. It came with a rumbling noyse, or low murmure like unto remoate thunder; it came from y^e^ norward and pased southward. As y^e^ noyse aproched nerer, the earth begane to shake and came at length with that violence as caused platters, dishes, and such like things as stoode upon shelves, to clatter and fall downe; yea persons were afraid of y^e^ houses them selves."

Five years later the town records of Newbury were increased by this item: "*June 1st.* Being this day assembled to treat or consult together about the well ordering of the affairs of the towne, about one of the clocke in the afternoone, the sunn shining faire, it pleased God suddenly to raise a vehement earthquake, coming with a shrill clap of thunder, issuing as is supposed, out of the east, which shook the earth and the foundations of the house in a very violent manner to our great amazement and wonder, wherefore taking notice of so great and strange a hand of God's providence, we were desirous of leaving it on record to the view of after ages, to the intent that all might take notice of Almighty God and feare his name."

In 1663 Massachusetts felt a series of shocks which in eastern Canada were severe—a real convulsion accompanied by landslides.

Matthias Plant, a minister at Newoury, wrote: "October 29, 1727 [old style], being the Lord's Day, about forty minutes past ten the same evening, there came a great rumbling noise; but before the noise was heard, or shock perceived, our bricks upon the hearth rose up about three quarters of a foot; and seemed to fall down and loll the other way, which was in half a minute attended with the noise or burst. The tops of our chimneys, stone fences were thrown down; and in some places . . . the earth opened and threw out some hundred loads of earth of a different color from that near the surface. . . . It continued roaring, bursting and shocking our houses all that night."

In 1755, 18 days after Lisbon was destroyed, New England suffered a shock which was felt as far as Maryland and Nova Scotia, and by the crew of a ship 70 leagues off Cape Ann. Twelve hundred chimneys of Boston suffered badly. Stone fences were thrown down, "especially on a line from Montreal to Boston." Springs were dried up; new ones opened. Sandblows issued from deep cracks in the ground. Fish in large numbers were killed in Massachusetts Bay by the shock to the water.

There have been many minor tremblings since. On March 21, 1904, a shock strong enough to throw down chimneys in

Eastport, Maine, and Saint Stephens, New Brunswick, was felt generally throughout New England and the maritime provinces of Canada—a total area of about 300,000 square miles. The recent quake of February 28, 1925, centering north of the Saint Lawrence Valley below Quebec City, about half-way between

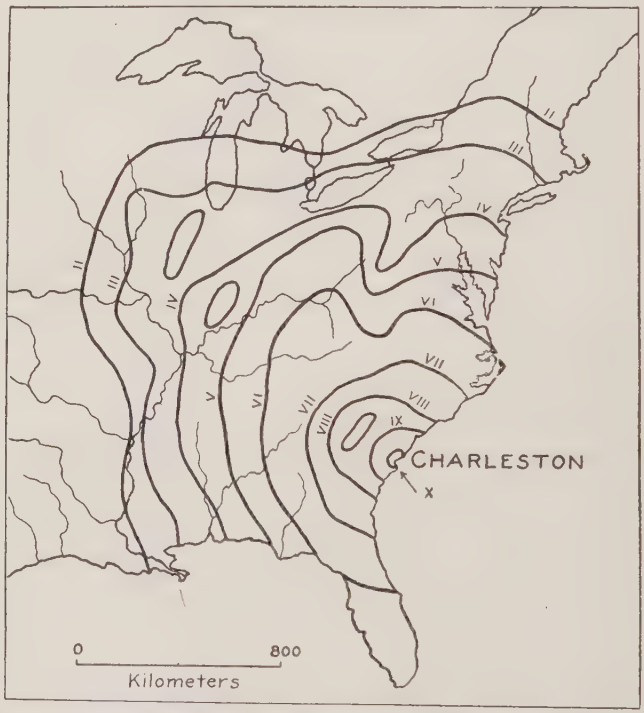


FIG. 7. ISOSEISMALS OF THE CHARLESTON EARTHQUAKE, 1886; ROSSI-FOREL SCALE OF INTENSITIES.

Murray Bay and Chicoutimi, was felt over an area twice as great. In each of these two cases the disturbance also affected a large but unmeasured part of the floor of the open Atlantic. Great as were the areas affected, the damage occasioned by either shock was slight. Sparseness of population at the centers of the disturbed areas can not wholly explain this remarkable fact, which is perhaps to be directly connected with the considerable depth of the locus, or point of origin, of each of the two earthquakes.

During recent years many slight local shocks have affected

Virginia, Tennessee, Missouri, and other States of the Union east of the Mississippi. South Carolina has had a special share. The Charleston earthquake of 1886 was truly great, though not

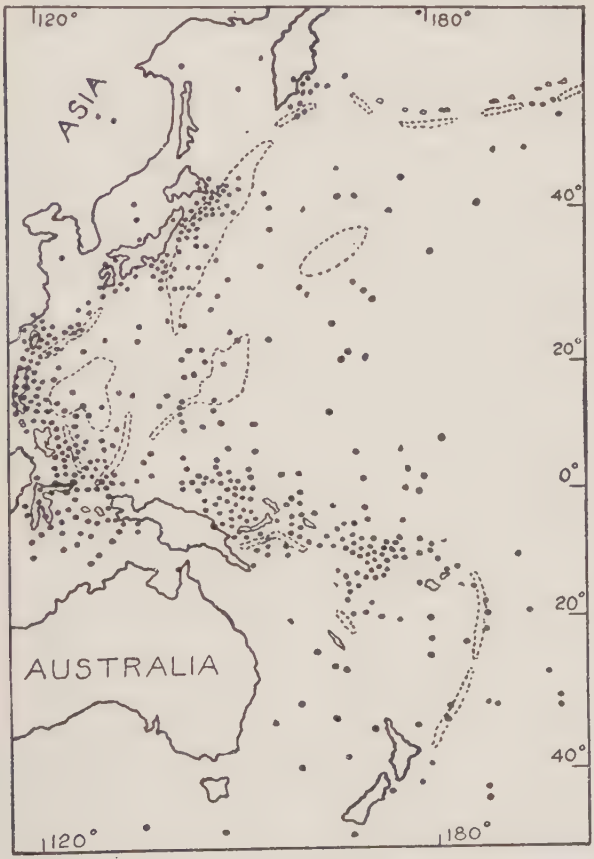


FIG. 8. EPICENTERS (LARGE DOTS) AND OCEAN DEEPS (DOTTED ISOBATHS) OF THE WESTERN PACIFIC. (After Montessus de Ballore, in "La Géologie Sismologique," A. Colin, Paris.)

of the first class. It was felt in Bermuda, 950 miles from the center of disturbance. Its tremblings were sensible over an area approaching 2,000,000 square miles. In Figure 7 the isoseismals (lines of equal quaking) show the progressive weakening of the earthquake wave as it spread outward from the center of shock near Charleston.

The luck of locality belongs to most of the United States, to Canada, northern Europe, northern Asia, most of Africa, Brazil, and Australia. California, with its steady record of from 50 to 100 earthquakes a year, takes the brunt of our dangers from the circum-Pacific belt.

The damage to mankind is obviously a direct function of the density of population. The fatal shock of 1891 centered in the Garden of Japan, where about 800 persons per square mile carried on intensive farming. The 30,000 casualties matched the complete demolition of 204,000 houses. On the other hand, much heavier shocks than any of those known to have originated in Japan have centered on or near shores with sparse population, like Alaska, South America, and the Pacific islands. Earthquakes of the first rank tend to be most numerous in the crust under the ocean, where the human population is zero. This fact is illustrated by Figure 8, which indicates the determined centers of shocks within the area of the western Pacific during a period of years. The map of the human disasters is, therefore, far from being also a map of either acute or chronic earthquaking.

The seismic damage to a city is markedly controlled by the character of the city's foundation. The most dangerous foundation of all is made ground, though not much more so than thin alluvium or thin layers of any other weak natural material. Destruction has been most terrible in those parts of Valparaiso, Kingston, Messina, and San Francisco which are underlain by thin, loose sedimentary deposits. Tokyo, Yokohama, and Mendoza (Argentina) have suffered specially for this reason.

If an earthquake as strong as that of 1755 should affect Boston, the Back Bay district and similar areas of made ground would be specially shaken. Some chimneys would probably fall, and cracks would be developed in many walls. The energy of the shock would, however, be relatively small, and there is no reason to think that a great disaster would ensue. In fact, while Boston is practically certain to feel slight tremors in the future, as it has felt them in the past, neither the history of the city nor

the geology of New England warrants alarm for the safety of this city from grievous seismic damage.

New York, built on a strong crystalline formation, is fortunate. Moreover, our largest city is far removed from any line of important geologically recent displacements of the earth's crust. Hence New York seems to be at least as immune from earthquake violence as London. Incidentally, it may be remarked that an astronomer's recently published statement of increasing danger to New York from earthquakes is based on absurd reasoning, and can not be too strongly deprecated. Such statements may yet work mischief in raising the premium rates of fire insurance companies for New York City.

In view of the fact that seismicity is usually strong in regions where it is chronic, a recent statistical study by R. H. Finch, of the Hawaiian Volcano Research Association, is of interest. During the nine years from 1915 to 1923 inclusive the United States was affected by 955 earthquakes, distinct enough to be

TABLE III

	NUMBER OF SHOCKS (1915–1923, INCLUSIVE)		NUMBER OF SHOCKS (1915–1923, INCLUSIVE)
Alabama	8	Nevada	36
Arizona	20	New Hampshire	2
Arkansas	12	New Jersey	2
California	594	New Mexico	4
Colorado	19	New York	10
District of Columbia	1	North Carolina	5
Georgia	2	North Dakota	1
Idaho	15	Oklahoma	1
Illinois	29	Oregon	17
Indiana	7	Pennsylvania	2
Iowa	2	South Carolina	17
Kansas	3	South Dakota	6
Kentucky	16	Tennessee	28
Maine	7	Texas	2
Maryland	1	Utah	36
Massachusetts	3	Vermont	1
Michigan	4	Virginia	6
Minnesota	2	Washington	37
Montana	5	West Virginia	1
Mississippi	4	Wisconsin	3
Missouri	20	Wyoming	13
Nebraska	1		

perceptible. According to the United States Weather Bureau, these shocks were distributed over 42 States of the Union. The number of shocks felt in each State is given in Table III.

Finch writes:

"As several of the earthquakes were felt in more than one State, they were counted more than once, so that the sum of the numbers in the above table exceeds the actual number of separate earthquakes. Over half of the earthquakes were reported from California, but this is not surprising when one considers the great extent of the State and the fact that it is the most active region seismically in the United States.

"The most active regions seismically in the eastern United States are along the middle part of the Mississippi River—southern Illinois, western Kentucky and Tennessee, northeastern Arkansas, and southeastern Missouri—and the southern Appalachians. Some of the earthquakes experienced in these regions caused minor damage; though the areas affected were nearly as great as the area affected by the San Francisco earthquake of 1906. This indicates that the actual breaks that cause the earthquakes are, as a rule, at a greater depth below the earth's surface in the eastern part of the United States than in the western part.

"During the first part of the nine-year period under discussion, several earthquakes were experienced yearly at or near Charleston, South Carolina, but during the latter part of the period the frequency of earthquakes at that place seems to have diminished.

"The strongest earthquake during the nine-year period occurred in Nevada on October 2, 1915. It was the strongest earthquake that has occurred in the United States since the San Francisco earthquake, and was recorded on seismographs all over the world. Cracks 22 miles long were opened in the earth's surface, but little damage was done, however, as the break occurred in a sparsely settled country."

The table indicates: (1) the great contrast of California with

respect to all the rest of the country; (2) the degree of chronic seismicity of the western Cordillera; and (3) the comparative freedom of New England and New York State from earthquakes. The general rule connecting the severity of shocks with their frequency in a given region seems, then, to warrant belief that the eastern United States is seismically in no danger comparable with that of the Far West.

The fact that the northeastern part of the United States felt, in 1755, an earthquake described as No. VIII on the Rossi-Forel scale of intensities, should be rated at no more than its real importance. According to the Rossi-Forel scale there are only ten numbered classes of intensities. The most powerful shock on record enters class No. X. To the uninitiated it might appear that a No. VIII earthquake is something like 80 per cent as dangerous as a No. X. As a matter of fact, under otherwise similar conditions, the destruction by a No. VIII shock is likely to be no more than a fraction of one per cent, or at most five or ten per cent, of the destruction due to a first-rank shock of the No. X class. From this point of view the Rossi-Forel scale is highly misleading. For example, prophecy that Boston is in danger of a real disaster of the San Francisco or Tokyo type, prophecy based on the occurrence of the No. VIII earthquake of 1755, in Massachusetts, is certainly not warranted.

Finally, the improbability of major seismic disaster to the large cities of the Northeastern States is suggested by another fact. There is practically complete absence of important recent fracturing of the earth's crust in that region. The next chapter will sketch the facts showing that, in an area subject to heavy earthquakes, some of those shocks have resulted from sudden rupture of the crust; that along the more or less vertical fractures displacements have taken place, with the generation of low cliffs or rifts in the rock. These topographic features are commonly only a few feet in height, but are many miles in length, and conspicuous to the trained geologist. Such scarps are well known in Japan, China, Formosa, California, Nevada, Mexico, India, New Zealand, and other countries that are plagued with

earthquakes. Thus, of the whole number of strong shocks in any of the regions, some of the shocks, though by no means all, leave enduring visible records in the bedrock topography. Now not a single long clifflet of the kind, clearly due to sudden rupture and displacement of the rocks during the last 5,000 or 10,000 years, is known in the United States east of the Mississippi River. To the geologist, therefore, no other reason is needed to make him sceptical of forecasts of very serious damage to New York, Boston, or any other Eastern city of the United States.

Other things being equal, the amount of damage done by an earthquake of course depends upon the amount of energy released. For a given depth of focus or point of origin for the shock, the quantity of this energy is roughly indicated by the extent of the area which is sensibly shaken. The mapping of the area is based upon the testimony of observers, and the accuracy of the map must vary with the density of population and with the alertness and scientific power of the people. Information as to the spread of the sensible disturbance under the ocean is specially meagre. For several reasons, then, few maps of seismic intensity can be classed as accurate in high degree. Yet the areas and distances given in Table IV are not far from the truth.

TABLE IV

AREAS SENSIBLY SHAKEN

REGION; DATE	STRONG MOTION (SQUARE MILES)	FELT MOTION (SQUARE MILES)	MAXIMUM DISTANCE FELT (MILES)
Mississippi Valley, 1811....	50,000	1,000,000	1,100 (Boston)
Naples, 1857.....	9,000	39,000	150
Charleston, 1886.....	100,000	2,000,000	950 (Bermuda)
Sonora, Mexico, 1887.....	?	400,000	?
Japan, 1891.....	50,000	330,000	400
India, 1897.....	160,000+	1,750,000+	1,000
Maine, 1904.....	?	300,000	400
California, 1906.....	25,000	370,000	350
India, 1907.....	120,000	1,000,000+	1,100
Messina, 1908.....	2,000	?	70
Ischia, 1883 (volcanic).....	5	10	2

The reader will note, on the one hand, the great energies of the shocks which have affected the Mississippi Valley, the Charles-

ton district, and India; on the other hand, the relatively minute energy indicated for the 1883 shock to the island of Ischia, off the Italian coast. Though the latter earthquake killed thousands of persons, it was of volcanic origin and different from all the others named in the table. The origin of these greater shocks will be considered in the next chapter.

From the area disturbed during the California earthquake of 1906, Professor H. F. Reid has calculated the absolute amount of energy then released. The calculation is founded on an assumption as to the depth of the rock layer which was moved during the shocks, and the result is, therefore, somewhat uncertain. Nevertheless, Reid's figure gives the order of magnitude as 130,000 million million foot-pounds, or the amount of energy required to raise a cubic mile of rock through a vertical distance of about 6,000 feet. The inconceivable power may be compared with that of the muzzle energy of America's most powerful gun, the coast-defence gun, which at the moment of discharge releases energy sufficient to raise a ton vertically fifteen miles. The 1906 earthquake was 800 million times as energetic.

Table V

Energy of Earthquakes

California, 1906....130,000 million million foot-pounds (Reid); equal to 800 million times muzzle energy of the greatest cannon; or to energy required to raise 1 cubic mile of rock 6,000 feet.

Relative energies of different earthquakes:

California, 1906, taken as 1; then (according to Sieberg)

Japan, 1891, energy	about	1¼
Lisbon, 1755, energy	"	11
Mississippi Valley, 1811, energy	"	15
Turkestan, 1911, energy	"	26
Pamir landslip, energy	"	1/1000

The California earthquake was not of the first class. Let its energy be taken as unity. Then the computed energies for more powerful shocks may be expressed as multiples of this unit, as shown in Table V.

Comparison with the energy of a gigantic landslide is illuminating. On February 18, 1911, at Sarez, in the Pamirs of central Asia, a mass of rock containing 3,270 million cubic yards and weighing about 7,000 million metric tons, suddenly fell through a height of 900–1,800 feet, or about 300–600 meters. The energy of this blow to the earth has been computed; it was about 1/1000 of the energy of the 1906 California earthquake. Though so much less powerful, the rock-fall set up vibrations in the earth's body which were registered by a seismograph at Pulkovo, nearly 2,000 miles to the westward.

Let us now look at an earthquake more in detail, in order that we may better understand why it does damage. The fall of structures is chiefly responsible for the loss of life. The collapse of structures evidently depends upon the kinds of motion of the ground. What are these kinds?

At and for some distance away from the center of shock the felt motions are complex and defy analysis, except as the result of much labor expended on instrumental records. After prolonged study of the records made by a Japanese earthquake, Professor Sekiya was able to construct a wire model, which showed the kind of path traced by a particle of the surface rock during the main series of shocks. The path was found to be of indescribable complexity, the motion of the particle having been in three dimensions and highly irregular. A picture of this model is to be found in several books dealing with earthquakes.

Within a few seconds the vertical motion becomes strong, as if the ground had been struck by the powerful upward blows of a monstrous hammer. The force of the blows can be gauged by comparison with the force of gravity. We estimate force by the acceleration it causes on a given piece of matter. By acceleration is meant the rate of increase of velocity and is expressed by physicists as so many millimeters per second per second. The accelerations of objects displaced during certain well studied earthquakes are stated in Table VI.

Table VI

ACCELERATIONS OF PARTICLES IN EARTHQUAKES

EARTHQUAKE	ACCELERATION, MILLIMETERS PER SECOND PER SECOND	EARTHQUAKE	ACCELERATION, MILLIMETERS PER SECOND PER SECOND
Japan, 1891	4,000+	Messina, 1908	2,000
India, 1897	19,000+	Maximum, probably	20,000+
India, 1905	3,500	Gravity, approximately	9,800

The accelerations corresponding to the intensities of shock by the Rossi-Forel scale are approximately as follows:

Class I.	2.5	millimeters per second per second.
II.	2.5–5	" " " " "
III.	5–10	" " " " "
IV.	10–25	" " " " "
V and VI.	25–50	" " " " "
VII.	50–100	" " " " "
VIII.	100–250	" " " " "
IX.	250–500	" " " " "
X.	500–20,000+	" " " " "

These figures embody one of the reasons for the need of caution in using the Rossi-Forel scale as a basis for estimating danger from earthquakes. We have already seen that a No. VIII shock is a very different thing from a No. X shock.

The accelerations due to the greatest shocks probably well surpass 20,000 millimeters per second per second, or roughly twice the acceleration of gravity. When the acceleration in the vertical direction is greater than that of gravity, loose objects jump into the air. Thus stones are seen to be tossed up and down "like peas on a drum." Boulders are thrown vertically out of their beds, and monuments from their sockets, as illustrated in Figure 9. This monument of the drawing, initially vertical, was shot upward and to the right, its base describing the course indicated by the broken line. When the heavy stone reached the soil, it made a strong indentation, and then fell over to the right.

During the Calabrian quake of 1783, a stone well was shot up about eight feet out of the ground.

Along with the vertical motion of the ground comes a series of to-and-fro horizontal jerks. These change direction rapidly. The combination of swiftly changing motions produces turmoil

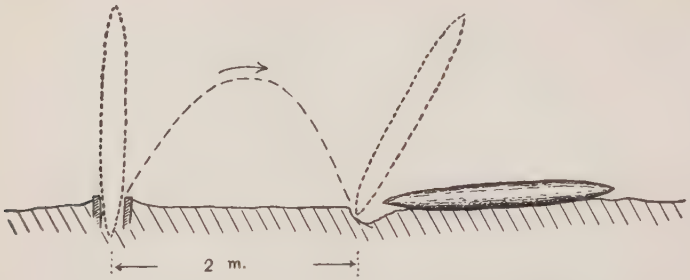


FIG. 9. THROW OF A STONE MONUMENT BY THE EARTHQUAKE OF 1897 IN INDIA; SCALE IN METERS. (After Oldham.)

analogous to that of a choppy sea. If monuments are not overturned, they are commonly rotated, as illustrated in Figure 10 (left). Figure 10 (right) also represents the quasi-vortical movement of the ground itself.

The blows, sudden drops, jerks, and twists are remarkably

FIG. 10. TORSION OF A MONUMENT AND OF THE GROUND DURING THE 1897 EARTHQUAKE IN INDIA. (After Sieberg and Oldham, by Permission of G. Fischer, Publisher.)

painful, and in many cases soon nauseate the observer, whose nervous tension grows still more rapidly.

The amounts of actual movement of the ground near the

centers of disturbance have been measured in several instances. We feel the vibration of the ground when the motion of its individual particles is only 1/1600 of an inch. When we think of the magnitudes of the swings given in Table VII—motions from 10,000 to 20,000 times that which is just sensible—we do not wonder at the description of one observer of the 1897 earthquake in India, who wrote: "The ground was shaken like a rat by a terrier." We can understand why the tops of chimneys are snapped off, trees and pinnacles are thrown down, and walls of

TABLE VII

ACTUAL TO-AND-FRO MOTION OF GROUND DURING EARTHQUAKES

EARTHQUAKE	VERTICAL SWING OF PARTICLE (INCHES)	HORIZONTAL SWING OF PARTICLE (INCHES)
Japan, 1891	4	14
India, 1897	?	9
Japan, 1894	?	6
Range of motion of particle, giving sensible shaking	....	1/1600

masonry leveled. The destructive effects are intensified if the natural period of vibration of chimney, tree, pinnacle, or wall agrees with the period of vibration of the ground. For then we have resonance; that is, progressive increase of the swing of the endangered structure.

The completeness with which a building is wrecked depends on the direction of the destructive force, as well as on its intensity. The effects on a house vary according as the impulse is vertical, parallel to the ridge of the roof, transverse to the ridge, or in some intermediate direction. The last case is illustrated by the Leland Stanford memorial arch (Figure 11), where the impulse was like that of a catapult and threw off the corner on the right. On a larger scale the fronts of city buildings are catapulted into the streets, causing a high proportion of the fatalities in many a major catastrophe.

Visible surface waves in the ground have often been reported by observers near seismic centers. They are analogous to water

waves. They may reach heights of from 1 to 2 feet, and lengths of 30 feet or more. The ground so waved may not return to its original form. The stony waves are sometimes preserved, stereotyped, as in the case of the Messina pavement, sketched in

FIG. 11. MEMORIAL ARCH AT LELAND STANFORD UNIVERSITY AFTER THE EARTHQUAKE OF 1906.

Figure 12. In 1906 the San Francisco streets were similarly thrown into swells and hollows.

The seismic waves are accompanied by compression of the ground. As a result of the Japanese quake of 1891, plots of ground, originally 48 feet long, measured only 30 feet after the shock. A compression of one to three per cent across river beds had to be allowed for in the rebuilding of bridges. Railways were bent sharply, like wriggling serpents. In San Francisco, pavements were compressed into arches which burst, and the under-

ground pipes of the water system of that city were telescoped (Figure 13).

In other places tension, the opposite of compression, leaves its marks. The root systems of large trees feel such tension, so that the tree trunks are sometimes split vertically and left with

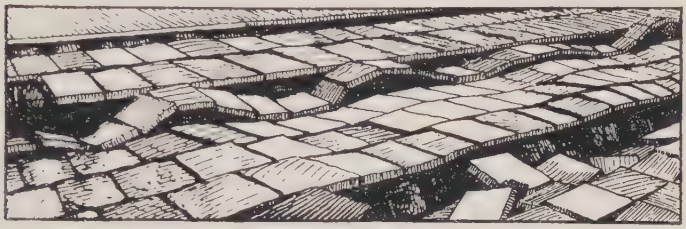


FIG. 12. FLEXURE OF A MESSINA PAVEMENT BY THE SEISMIC WAVES OF 1908. (FROM SIEBERG'S "ERDBEBENKUNDE," G. FISCHER, JENA.)

wide fissures, gaping downward. The San Francisco water pipes felt powerful tension locally, and were torn apart (Figure 14).

As a result of the complex movements, large blocks of the softer soil lurch forward bodily and do not return. This happened in San Francisco, where along certain streets plots of ground with buildings, sidewalks, and curbs lurched forward or backward in relation to the lines of the respective streets, and stayed there. Similarly, street railways are distorted through the lurching of the more mobile parts of their foundations.

Farther from the center of disturbance, or "focus," the visible motion of the ground gradually loses its infinite complexity and becomes more simply undulatory. The ranges of both vertical and horizontal motions of the ground become rapidly smaller, and, a few tens of miles from the origin, the ranges or amplitudes become less than one inch.

Seismic damage can be enormously lessened by proper construction of buildings. This important subject is much too broad for present treatment. We shall note only a few facts. The loss of life in Tokyo in 1923 was much increased by the general use of roof tiles, which were not well fastened. In consequence, mil-

lions of these heavy bodies were avalanched into the streets, killing the people and blocking the way of escape for survivors from the deadly showers. The unimaginable collapse of Messina in 1908, as in 1783, was not primarily due to the violence of the shocks, for the energy of neither of these earthquakes even approached the first magnitude. The 1908 quake did no harm to Catania, only 50 miles distant. The evil was in the almost universal use of rubble masonry in thick walls, which were feebly cemented with mortar; the building joists were merely inserted in shallow mortises and were not fastened. Some façades, of respectable masonry, stood up well, emphasizing the deep damnation of the average construction; for the most part Messina was made up of "human deadfalls."

That modern methods, especially the use of reinforced concrete and of proper methods of framing, bracing, and bonding, can greatly diminish the damage was illustrated at Tokyo, Messina, and San Francisco.

In passing, we may note the suggestion of Frech, the Austrian geologist, that the Byzantine style of church architecture was developed partly in relation to the pronounced seismicity of the eastern Mediterranean. In particular, the use of lateral half-domes, buttressing a central dome, was an effective solution to the problem of stability in a land subject to shocks. Saint Sophia is the stable monument to the foresight of Justinian's architect.

Natural structures, as well as artificial, are thrown down, or else stressed and weakened to the point where sliding or flow begins; as in Humboldt County, California, during the 1906 shocks (Figure 15). The fresh scarp of the hill in the background is the place whence came the disordered landslip material of the foreground.

During the Indian quake of 1897, landslides took place at intervals along hundreds of miles of valley walls. In one valley the walls were scarred for a length of 20 miles by the slipping of forest-covered soil and rock. Much sand was thus exposed. This was flooded over the stream valleys by the rains, causing very important damage to farm lands. Similar effects on a large

FIG. 13. TELESCOPING OF A 30-INCH WATER PIPE, NORTHWEST OF SAN ANDREAS LAKE, BY THE CALIFORNIA EARTHQUAKE OF 1906.

The thrust here caused telescoping to the extent of 58 inches.

Photographs by Lawson.

FIG. 14. TENSIONAL RUPTURE OF A 30-INCH WATER PIPE, NORTHWEST OF SAN ANDREAS LAKE, BY THE CALIFORNIA EARTHQUAKE OF 1906.

scale were observed during the 1811–1812 New Madrid earthquakes of the Mississippi Valley; cavings of the river bluffs were seen even as far away as Indiana, along the Ohio River. The sea cliffs and valley walls of Portugal were extensively affected by slides during the Lisbon quake of 1755. Other examples might

Photograph by Eakle.

FIG. 15. LANDSLIDE AT CAPE FORTUNAS, HUMBOLDT COUNTY, CAUSED BY THE CALIFORNIA EARTHQUAKE OF 1906.

be cited from the records of the Iceland (1896), Mexican (1887), Japanese (1891), and Owens Valley (1872) shocks.

The damage from landslides is obviously increased by the high relief of the country. In the year 1348 the Alps were shaken quite moderately; yet one of the resulting slides overwhelmed 17 villages. Probably the record for killing in this terrible way is held by the 1920 earthquake in the Kansu Province of China. This world-shaking jar, one of the most violent in history, centered in the loess region, which is characteristically and deeply dissected by steep-walled canyons and wider valleys. The loess, an ancient, somewhat cemented, thick deposit of dust, which had been blown hither from the deserts to the westward, is a

weak formation. So intense was the shaking that colossal masses of this material were precipitated into the valleys as chaotic, eddying landslides. In spite of the low density of population in this part of China, the number of persons overwhelmed has been estimated as more than 100,000. The number of deaths may have reached 200,000. The survivors said that the "mountains walked in the night."

When snow-capped mountains are severely shaken, avalanches are abundant. The heavy Italian earthquake of 1915 caused massive snowslides in the Alps, 300 miles from the center of shock. The stupendous blow to the earth in 1899, when mountains of Alaska jumped up 20 to 50 feet, caused numberless avalanches. That shock also changed the stresses in the Alaskan glaciers, which consequently flowed with remarkably increased velocity for several following years.

Some loss of life and property by engulfment in earthquake fissures has often been reported. One of the Calabrian fissures, which were formed in 1783, measured, after the shock, 200 feet in depth and 100 feet in width. A similar fissure in Iceland is 6 miles long, 45–75 feet wide, and 90 feet deep. Usually the gaping is not so great. The fissures visible in soft ground after a major shock defy counting. Many others are temporary only, opening and closing rhythmically as the earthquake waves pass. Into these men, cattle, even houses, are precipitated, to be smashed flat almost instantly with the completion of the oscillation. If we imagine the cracks opening and closing in rapid succession, we can appreciate the terror of men and animals.

To prevent engulfment during the 1811–1812 earthquakes, the settlers of the Mississippi flats are said to have mounted tree-trunks placed across the lines of the fissures. The Japanese are directed to flee to bamboo groves, where the tough interlacing roots of these trees prevent engulfment.

Permanent fissures are specially abundant along the edges of plateaus, river bluffs, canal banks, and escarpments generally. They are usually formed along the edges of cliffs which have yielded landslides. The rough, lacerated surface looks as if it

had been ruined by immense explosions of powder deep underground, and it long remains useless for farming. The innumerable cracks opened by the Japanese earthquake of 1891 produced local chaos, "as if gigantic ploughs, each cutting a trench from 3 to 12 feet deep, had been dragged up and down the river-banks."

Photograph by Branner.

FIG. 16. ROCK DÉBRIS EJECTED BY SEISMIC FOUNTAINS, AND ACCOMPANYING CRATERLETS; CALIFORNIA EARTHQUAKE OF 1906; NEAR MILPITAS.

The slumping and fissuring along the many canals enforced the heart-breaking task of repairing more than 300 miles of these vitally important structures.

A phenomenon of more purely scientific interest may be mentioned. A common incident in strongly shaken areas is the expulsion of water and water-charged sand (sand-blows) at points along the earthquake cracks. So rapid is the expulsion that the water makes fountains with heights of many feet. Round pipes are drilled by local enlargement of the fissures. Through the

pipes sand and water gush out, building craterlets like those pictured in Figure 16, products of the California quake of 1906. Twenty years before, other craterlets were formed during the Charleston quake.

Below the surface the fissures are often filled with sand which had been expelled from deeper strata during the paroxysm.

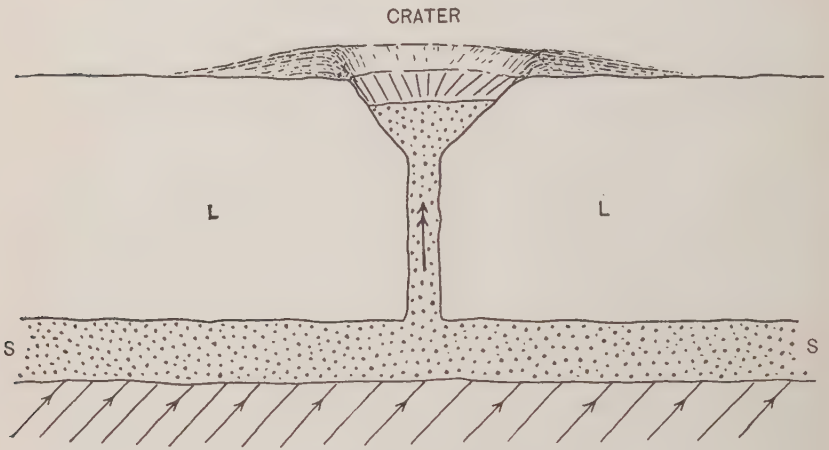


FIG. 17. DIAGRAMMATIC SECTION ILLUSTRATING THE ORIGIN OF SAND DIKES AND SEISMIC CRATERLETS.

These more or less vertical masses of injected sand are called dikes. Such sand dikes were injected into the Mississippi alluvium during the heavy shocks of 1811–1812.

These eruptive effects are explained by the compression of water-bearing strata and of weak sandy strata. The compressive force is due to the inertia of the rock-mass overlying each water-charged, sandy layer. In the diagram, Figure 17, the layer of water-bearing sand is shown at *S-S*. The direction of the seismic impulse is shown below by arrows with single barbs. The inertia of the heavy bed, *L-L*, causes compression of *S-S*. The more fluid constituent is spurted upward, as shown by the doubly-barbed arrow. The sand collects around the outlet pipe; hence the crater. Now one of the interesting things about these sand-filled pipes and fissures is that they are permanent records of

FIG. 18. A GROUP OF SANDSTONE DIKES OF SEISMIC ORIGIN; SHASTA COUNTY, CALIFORNIA.

The dikes cut gently dipping strata.

the earthquake, unless it should happen that they are eroded away. Many sand dikes, long ago converted into sandstone dikes, have been preserved by burial for millions of years; then exposed to view by erosion (Figure 18). From these exposures the geologist is able to tell that at as many localities there have been ancient earthquakes. By fossil evidence he is able to date

Photograph by Wood.

FIG. 19. POND FORMED BY SEISMIC DELEVELING ALONG THE SAN ANDREAS RIFT, SOUTHEAST OF MUSSEL ROCK, CALIFORNIA.

the respective formations. Thus we have learned that the earth was shaking long before man was evolved on the earth. It appears that our globe has always been under stress, ever since the crust was formed.

One other effect, which in certain cases has been of economic importance, may be noted. Underground dislocations of the rocks during a major earthquake can not fail to interfere with the delicate system of channels which before had fed springs. Hence, old springs are destroyed and new ones created. Warm springs

are changed in temperature. Examples are Trans-Caucasian springs near the Caspian Sea, which had their temperature raised from 44 degrees Centigrade to the scalding point because of an earthquake in 1848. The Icelandic shock of 1896 originated a temporary geyser, which threw hot water mixed with steam to a height of 600 feet; at the same time the famous Strokkr geyser was extinguished.

Changes in river drainage are caused by the landslides and by permanent warping of the ground. By the movements of the ground during the California quake of 1906, ponds were developed along the line of maximum displacement (Figure 19).

The tremendous Indian earthquake of 1897 was accompanied by a similar tearing-apart of the earth's crust, with local uplifts and sinkings and the formation of a chain of ponds along the main fracture.

Valuable ground for tillage may thereby be lost for use, at least temporarily. Swamps so generated in warm countries have led to serious epidemics of malaria.

According to John Milne, 3,000 persons died of sickness due to the emanation of noxious gases from fissures which were caused by the 1692 earthquake at Kingston, Jamaica.

Heavy earthquakes near shores regularly shock many fish to death. The Indian quake of 1897 killed countless thousands of fish, and even some dolphins in the Ganges River. So great was the mortality that the fisheries of the Indian rivers were poor during the following year. The sudden compression of the bodies of the animals and the bursting of their swim-bladders have often caused the wholesale destruction of marine fishes. Their carcasses, numbered by millions, may be seen floating on the surface. Their accumulated skeletons make "bone beds," like those explained by geologists as due to earthquakes of remote ages.

Since the sea bottom is often suddenly displaced by a shock occurring near the coast, seismic sea waves are produced. These run out in all directions. Like wind waves, they shorten and heighten as they reach shallow water. The maximum heights are determined by the initial displacement of water, by the ground

plan of the shore-line, and by the slope of the bottom. The great combing waves sweep over low shores and cause much damage. In 1899 such waves wrought havoc in the forests of Alaska. The 1908 shock at the Strait of Messina generated sea waves which were 8 meters high at Galati, in Sicily, and 10.6 meters high at Lazzaro, on the Calabrian shore.

Sea waves, famous in history for their destructiveness, are listed in Table VIII.

TABLE VIII

SEA WAVES DUE TO EARTHQUAKES

PLACE; DATE	HEIGHT ABOVE HIGH-WATER LEVEL	PERSONS DROWNED
Japan, 1293	?	30,000
Japan, 1703	?	100,000
Lima, Peru, 1724	80 feet	....
Callao, Peru, 1746	80 feet	....
Lisbon, 1755	60 feet	Many thousands
Calabria, 1783	?	1,500
Virgin Islands, 1867	23 feet	....
Arica, Peru, 1868	52 feet	....
Iquique, Chili, 1877	80 feet	....
Japan, 1896	50 feet	30,000
Messina, 1908	30 feet	....
Acapulco, Mexico, 1909	30 feet	....
Porto Rico, 1918	16 feet	....
Japan, 1923	37 feet	....

The size and energy of the initial wave may be appreciated from its effect on distant shores. An example is the wave developed at the Iquique center, facing the Andes, in 1877. This wave crossed the wide Pacific and registered heights of 6–12 feet in Samoa, 3–20 feet in New Zealand, and 5–10 feet in Japan. A seismic wave of somewhat similar dimensions had, in 1724, flooded Callao, Peru, sinking 19 out of the 23 ships there anchored, and carrying the rest far inland.

As Tokyo, Yokohama, and San Francisco know too well, fire caused by earthquakes may be more destructive to property than all other phases of this terror that walks by day and by night. Among the reasons for the collapse of the San Francisco water-supply system was the location of pipes, dams, and reser-

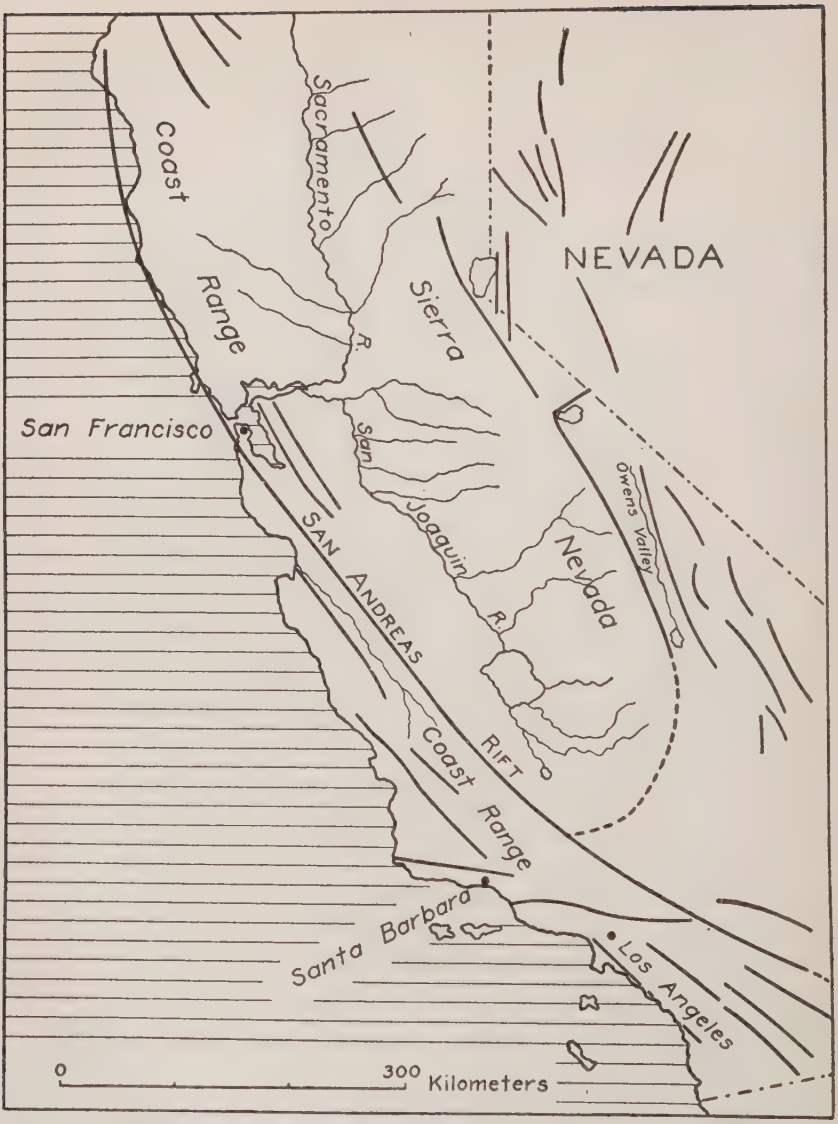


FIG. 20. MAP OF SOME OF THE MAIN FAULTS OF CALIFORNIA, SHOWING THE RELATION OF THREE CITIES TO THOSE FAULTS.

voirs of the system in the San Andreas rift valley itself, the very place where Thor's hammer fell. See Figure 20.

The Los Angeles aqueduct, the one water resource of a vast city, rainless for months together, is 238 miles long. Fifty-three

of those miles are in tunnels. The aqueduct crosses both the San Andreas rift line, where was struck the blow so fatal to San Francisco, and also follows for some distance the line where a yet stronger earthquake originated in 1872, centering in Owens Valley. The map (Figure 20) shows the positions of the San Andreas rift, of Owens Valley, and of Los Angeles. A small shock along the Owens Valley has already damaged the aqueduct, necessitating repairs. In 1922 it was broken by a shock originating in the adjacent Mohave Desert. In 1920 a damaging quake shook Inglewood, a part of Los Angeles itself; the fault responsible is said to be 85 miles long; it passes through the city. Clearly, Los Angeles must back its engineers in planning for safety from a general conflagration.

In all cities threatened with earthquakes, every effort should be made to secure the proper placing of gasoline stations and to provide for the speedy, preferably automatic, closing of the supply mains for illuminating gas and electric power.

Summary

The great earthquakes of history have, then, deep meaning for the humanitarian. Wise himself, he looks ahead in the light of the past. He has pondered the past, a past teeming with untellable disasters from earthquakes. The men of the past were so helpless because they were without science. Like the hard-headed man of business, the humanitarian sees that *all* men lose when Japan, Chili, India, or Italy loses through earth-shaking. We all help to pay the bill when the world's savings are destroyed and world markets dislocated. All peoples are interested in mitigating these catastrophes. The only possible mitigation comes from science. Men must first understand earthquakes.

This chapter contains a brief analysis of some of their effects. Illustrations of loss, in lives and material, have been called to memory. The place of danger on the globe has been reviewed. Certain zones are seen to be specially threatened. The cause of this concentration of tragedies is a subject of Chapters III, VII, and VIII. The importance of studying the kinds of rocks that

underlie the cities of the seismic belts has been proved by the sorrows of Messina, Valparaiso, San Francisco, Tokyo, and Yokohama. Danger from landslides should be evaluated. City fathers must study geology.

We have noted the new computations of the energy of an earthquake, making more definite to our minds the irresistible power of this enemy of mankind. We have glanced at the modes of seismic motion. City fathers must study physics.

The deadliest effect of an earthquake may be the breakdown of water supply, and a consequent conflagration. The proper location of reservoirs and pipe lines depends on the mapping of the districts where earthquakes originate. City fathers and engineers must study seismology.

Dwellers on low shores should be systematically taught what to do to save themselves from sea waves. Statesmen must study psychology and oceanography.

Thus, as usual, the wise providence of man demands more and more science. The humanitarian, the man of business, the man of public affairs, facing the earthquake problem, all have to bring their practical questions to the seismologist, the specialist who applies the principles of physics, geology, and engineering to his subject. In the next chapter we shall consider what the seismologist has discovered regarding the origin and true nature of the dangerous earthquake. The pure science of seismology is worth attention for its own sake. It is worth attention, inasmuch as its practical applications are to living men, women, and children, and to the millions of the future, more precious than rubies.

CHAPTER II

THE NATURE OF EARTHQUAKES

Throughout most of human history, natural convulsions have been thought to be direct acts of God or a god, the immediate as well as the final cause. A gallery of plutonic gods has been painted by the artistic priests of the past in order to back the popular belief. To our own day certain murderous shocks are remembered in special services at Japanese temples. The Lisbon earthquake of 1755, the severest known in European history, was explained by the English clergy as a divine stroke at the rampant Catholicism of the Portuguese capital. The Catholic survivors of Lisbon attributed their misfortune to the presence of Protestant heretics in their midst. These heretics were forcibly baptized into the Roman Church, in order to prevent a second punishment for the sin of tolerance.

To-day we do not presume to trace the chain of causes to finality; we must be content with mechanics and proximate causes.

An earthquake is a trembling, the passage of a series of vibrations through the earth's crust. Vibrations may be caused by a blow, as when a bell, a block of steel, or a drum is beaten. Our houses shake when a heavy truck passes, striking the pavement with each unevenness of the way. Or vibrations may be caused by sudden snapping of a solid mass which had been under tension. So we feel lake ice tremble when it snaps open on a cold winter day. The creeping glacier is under tension. When it suddenly cracks, we hear the vibrations of the air, like a gunshot. Or vibrations may be caused by movement of one body against another under friction, as when a violin is played. So a street-car trembles as it chatters its way along the rails. The earth trembles when struck by the blow of a powder explosion.

when suddenly cracked by tensional force, when rubbed by a gale of wind. Of these three modes, the vibration due to sudden fissuring under tension is the most important, but both sudden impact and friction are associated, contributory causes.

A century ago even strong earthquakes were attributed to the fall of large masses of rock from the roofs of caverns. This simple explanation was seen to be inadequate when it became clear that the energy of an ordinary earthquake is vastly greater than the energy released by any possible rock-fall of the kind.

Much stronger shocks can be delivered by landslips in mountainous regions.

Heavier blows still are struck during volcanic explosions. The world's record for a century was made at Krakatoa in 1883. Much of this large East Indian island was then blown up. The evisceration was so complete that the sea is now nearly 1,000 feet deep on the site of the original high island. The resulting earthquake was sensible only to comparatively short distances. This effect on the earth's crust was so small for the reason that most of the energy was expended in shocking the ocean and atmosphere, as well as in the comminution of rock. On the other hand, the sea waves generated by the explosion reached heights of 100 feet, drowned 36,000 persons on neighboring shores, and were still able to affect tide-gauges at distances of 5,000 miles. The sound of the explosion was heard at Rodriguez Island, 3,000 miles to the westward. In fact, the atmosphere was struck such a blow that the air waves were registered by barographs during three complete journeys round the globe.

Earthquakes have often been occasioned by sudden rearrangements of the rocks, solid and liquid, at volcanic centers, without explosion. The Italian island of Ischia has often been afflicted by quakes of this kind. One of them, in 1883, killed 2,000 persons. This case illustrates, however, the relatively small energy of the volcanic earthquake. As shown in Table IV (page 22), the strong shocks were confined to an area of only about five square miles. The trembling was felt over an area which was little more than 10 square miles. The respective figures for the non-volcanic

earthquake of India, in 1897, are 160,000 and 1,750,000 square miles.

All four kinds of earthquakes pale to insignificance when compared with the remaining class. These are called *tectonic* because the shocks are caused by the relief of elastic strain in the solid body of the earth, particularly in the crust, a complex

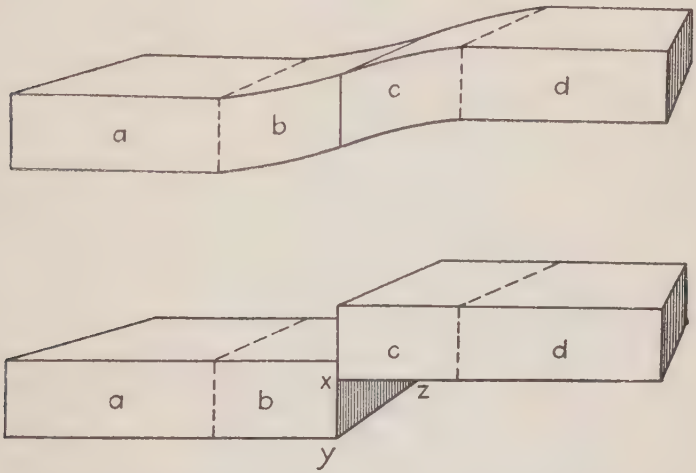


FIG. 21. TENSIONAL STRESS IN A BENT SLAB AND ITS ULTIMATE FRACTURE (FAULTING). (After Sieberg in "Erdbebenkunde," G. Fischer, Jena)

piece of "architecture," which, like an artificial building, is kept constantly strained by the force of gravity.

The crust, made of ordinary rocks, has considerable rigidity, or stiffness, and strength. It has been, and is, subjected to forces which cause the crust to be compressed in some places and dilated in others. Hence the crust is not in a state of ease, but is in a state of stress. The forces tending to distort or reshape the earth are resisted by the elastic strength of the crust. The diagram of Figure 21 may help our thought. Imagine a slab of rock to have been bent without breaking into the shape *a-b-c-d*. The amount of bending shown is greater than a common rock could stand without breaking, but this exaggeration, introduced for clearness, does not affect the principle involved. Elastic forces,

analogous to those of a wound-up steel spring, have accumulated during the slow march of geological time. With sufficient accumulation the elastic strength of the rock slab is overpassed. Along a plane, here shown as vertical, the rock snaps; the block *b* slips with chattering friction against the block *c* along the fracture *x-y-z*. The sudden fracture of the earth's crust and the rapid movement under friction set up elastic waves—a train of them, which spread out in all directions.

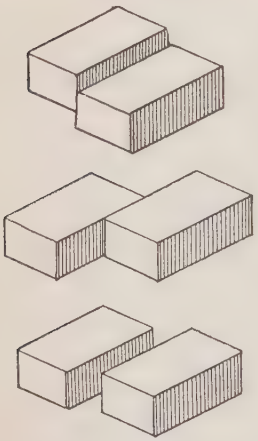


FIG. 22. MODES OF FAULTING. (After Hobbs.)

So when one breaks a long stick, the ends held in the hand vibrate, often with painful energy.

The interfaces along which the masses of rock move when they break are called technically fault planes. The place of scission is called a fault. Figure 22 illustrates, at 1, fault movement in the vertical direc-

FIG. 23. FAULT SCARP FORMED DURING THE JAPANESE EARTHQUAKE OF OCTOBER 28, 1891. (After Sieberg and Kotô, by Permission of G. Fischer, Publisher.)

tion; at 2, in the horizontal direction; at 3, simultaneously in both senses.

The interface of sudden fracture may crop out at the earth's

surface. The drawing of Figure 23, from a photograph, shows the fault scarp produced when Japan received its heavy jar

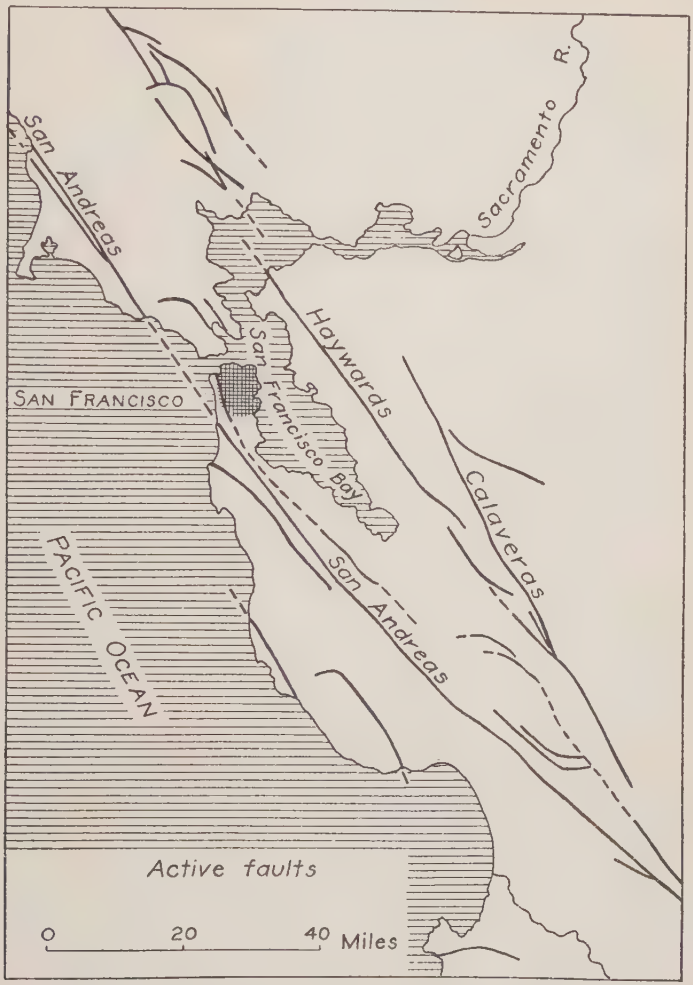


FIG. 24. MAP OF SEISMICALLY ACTIVE FAULTS (THICK LINES) IN THE VICINITY OF SAN FRANCISCO.

in 1891. We see how strata, originally flat and continuous, have been bent and shattered. A similar fault scarp was suddenly developed near Winnemucca, Nevada, in 1915; the region was strongly shocked.

Since it takes some time for a fault to reach its full extension, a series of shocks and many trains of elastic waves are generated. The main blows and jerks are accompanied by friction, also responsible for some of the vibrations.

Only within the last few decades has the fault, or tectonic, origin of nearly all important earthquakes become clear. The evidence is too technical to be displayed fully in this book, but the matter is so vital that we may well glance at a few illustrations.

The account of the California earthquake of 1906, issued by the State Earthquake Investigation Committee (1908), is unique for wealth of detail. This shock was due to the sudden formation of a single fault. The fracture has been traced for a distance of 190 miles, southeastwardly from Point Arena, which is 110 miles northwest of San Francisco. The total length of the fault was greater, for it almost certainly continues under the Pacific water, and crops out on the land again at a point 80 miles to the northwest of Point Arena. Well marked along San Andreas Valley, the dislocation has been called the San Andreas Fault. As the map (Figure 24) shows, it runs parallel to a number of other faults, recently formed in the mountains of California.

A few photographs will illustrate the breaking of the surface of the ground along the 190 miles of the fault actually traced. The first view (Figure 25) was taken a mile northwest of Olema, looking south. In this instance the appearance of vertical displacement is largely due to the combination of horizontal displacement with the slope of the ground. Across hill and valley, mountain and plain, the fracture pursues its way, indifferent to topography. In many places the fault trace is exhibited as a narrow belt of fissures. Elsewhere the belt is broader, and often the investigating geologists were at a loss to distinguish the trace of the primary fault from those of the secondary faults, that is, those along which the rocks were ruptured and displaced by the passage of waves from the primary fault. An example is shown in Figure 26, a photograph of a group of displacements southwest of Pine Gulch Creek. The picture was taken some time

Photograph by Gilbert.

FIG. 25. FAULT SCARP CAUSED BY THE 1906 DISPLACEMENTS ALONG THE SAN ANDREAS RIFT, ONE MILE NORTHWEST OF OLEMA; LOOKING SOUTH.

Photograph by Gilbert.

FIG. 26. GROUP OF EARTHQUAKE CRACKS FORMING A BELT ALONG THE SAN ANDREAS RIFT, SOUTHWEST OF PINE GULCH CREEK.

after the dislocation. The field had already been ploughed and the farm road had been graded up the fault scarps; nevertheless the structure is well indicated, especially in the foreground and along the sky-line.

Photograph by Eakle.

FIG. 27. THE SAN ANDREAS RIFT NEAR ITS NORTHERN END; WOOD GULCH, HUMBOLDT COUNTY.

The primary San Andreas faulting was a movement along a nearly vertical interface, where similar displacements had occurred at intervals during thousands of years. This oblique slicing of California, so often repeated along the same line, had formed a well marked, narrow depression or line of scarps, from Point Arena through the State, via the Tejon and Cajon passes,

to the Colorado Desert. The whole line of topographic features is called the San Andreas Rift. The narrow belt of multiplied dislocations has been traced with three interruptions from Humboldt County to the Colorado Desert, a distance of over 600 miles. Indeed the California geologists think it not impossible

Photograph by Fairbanks.

FIG. 28. FAULT SCARP IN THE SAN ANDREAS RIFT; MOJAVE DESERT, WEST OF BIG ROCK CREEK.

that this major seismic belt extends through Mexico and Guatemala to Jamaica.

Figure 27 is a photograph of the rift near its northern end, at Wood Gulch. Here it consists of a narrow depression with ponds, ridges, and saddles, and along the axis of the depression the fresh trace of the 1906 dislocation of the earth's crust was discovered. The shock of the faulting was so violent as to cause great landslides in the immediate vicinity and along the coast. Erosion by rain and wind had softened the clifflets due to the older displacements, but the origin of the rift was already clear to geologists before the year 1906.

Photograph by Lawson.

FIG. 29. OFFSET IN 30-INCH WATER PIPE BY THE 1906 FAULT AT THE SAN ANDREAS RIFT; NORTHWEST OF SAN ANDREAS LAKE.

Photograph by Branner.

FIG. 30. OFFSET OF SIX FEET IN FENCE BETWEEN SAN ANDREAS AND CRYSTAL SPRINGS LAKES, BY THE 1906 CALIFORNIAN EARTHQUAKE.

Figure 28 shows the fault scarp marking the rift far to the south, in the Mohave Desert west of Big Rock Creek; the cliff is about 40 feet high. There, as elsewhere along the rift, the proof of movements before the year 1906 is given also by ponds along

Photograph by Gilbert

FIG. 31. TWENTY-FOOT OFFSET OF ROAD NEAR POINT REYES STATION, BY THE 1906 CALIFORNIAN EARTHQUAKE.

the depression, these older ponds having already existed before the 1906 faulting.

The renewed displacement which so powerfully shook central California that year was compound. The principal movement was horizontal, the great crust-block on the northeast moving southward with respect to the block immediately southwest of the rift. The relative shift of the earth's crust was not uniform. Thus the water pipe, shown in Figure 29, was broken and offset only about 18 inches by the fault. For the greater part of the rift, the horizontal displacement was about 10 feet. At many points it was over 15 feet, and at one place it was 21 feet.

These values were obtained by measuring offsets of fences and roads (Figure 30). The fence pictured was originally

straight; it is situated between San Andreas and the Crystal Springs Lakes. The offset was here six feet. The fault shifted the foreground that distance to the left with relation to the part of the fence in the background. The road shown in Figure 31 was originally straight; it runs southwest from Point Reyes Station and was offset 20 feet.

Trees, meadows, farm buildings, railways, mountains, whole counties accompanied the 1906 movements when California was sliced.

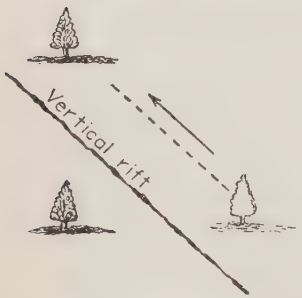


FIG. 32. DISPLACEMENT AT THE NEO VALLEY RIFT, JAPAN. (After Hobbs and Kotô, by Permission of D. Appleton and Company, New York.)

Similar sudden horizontal shifting of blocks of the earth's crust was responsible for the violent Japanese earthquake in 1891, one of the evidences being the displacement of trees, illustrated in Figure 32. Before this faulting took place, the tree indicated in the upper part of the diagram was in the position of its ghost, lower down and to the right. The relative displacement was in the direction of the arrow, parallel to the vertical plane of rifting, shown in the drawing.

The vertical displacements along the San Andreas Rift were much smaller than the horizontal displacements, probably nowhere exceeding three feet.

An explanation of this 1906 earthquake is now in sight. It has been best described by Professor H. F. Reid. For many years previously the earth's crust in California had undergone a progressive strain. Geological forces were tending to shear the State into two parts. A broad strip of land, northeast of the rift, tended to move to the southeast. A broad strip of the crust, southwest of the rift, tended to move to the northwest. For years these growing tendencies were resisted by the strength of the crust. At last, at a certain moment of the year 1906, the forces reached the elastic limit of the crust. The crust broke at a point. With the speed of sound in rock, that is, at the rate of over three miles a second, this incipient fracture spread along

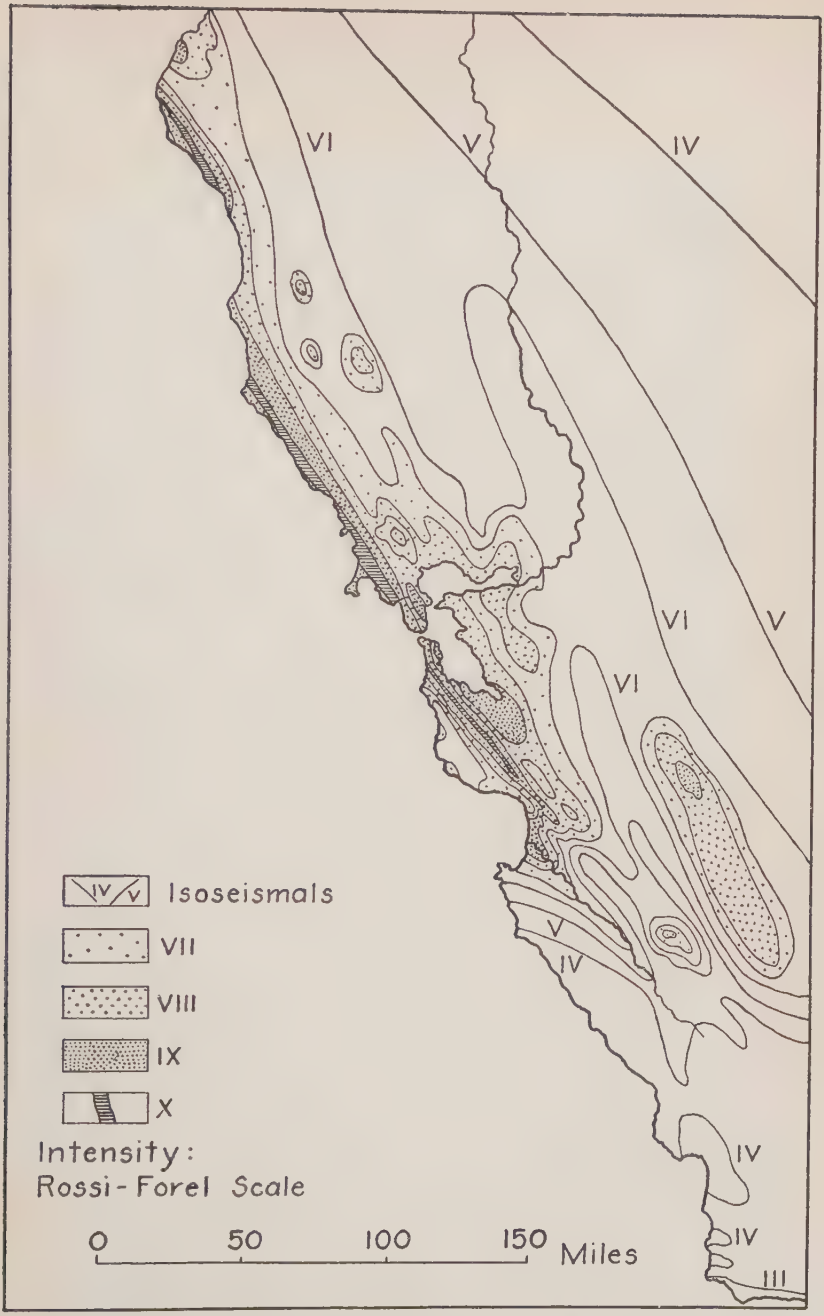


FIG. 33. ISOSEISMAL LINES OF THE CALIFORNIA EARTHQUAKE OF 1906.

the line of the San Andreas Rift. In a minute or two of time the long fault was formed. The crust was relieved of strain which had long been growing. The crust bounded back toward its

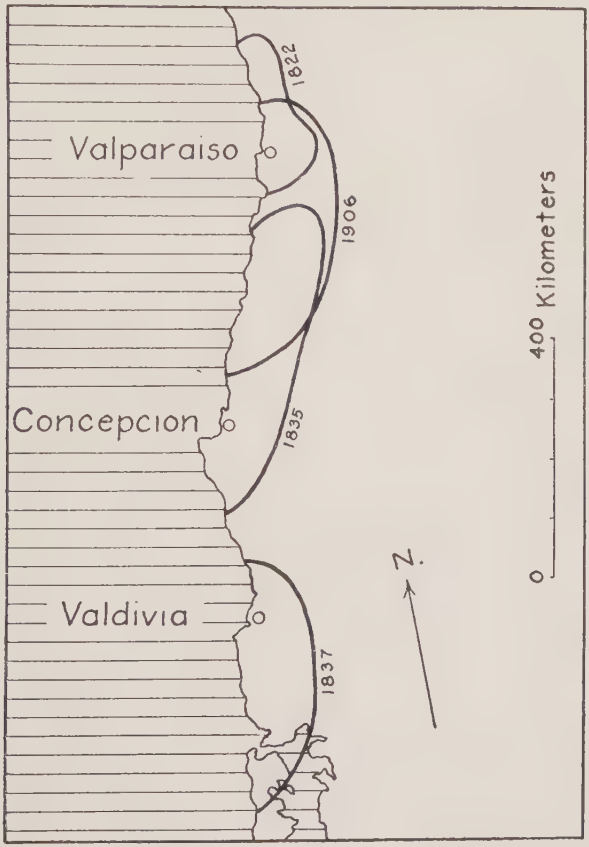


FIG. 34. AREAS OF SENSIBLE SHOCK IN VARIOUS CHILIAN EARTHQUAKES. (After Montessus de Ballore in "La Géologie Sismologique," A. Colin, Paris.)

original position, and that so suddenly as to jar the whole State of California and, in fact, the whole earth.

This explanation of the California earthquake implies that the belt of destruction should be elongated parallel to, and close to, the San Andreas Rift. Likewise the areas bounded by the isoseismals, or lines of equal shaking, should be elongated and placed more or less symmetrically along the rift. On the map

(Figure 33) the lines bearing Roman numerals are isoseismals, classed according to the Rossi-Forel scale of intensities. Where the trembling was greatest, the intensity is represented by shading, the depth of which is roughly proportional to the vigor of the displacements of the ground. The areas within the inner isoseismal lines have lengths which are several times the respective widths; the rift is clearly the major axis of the principal area of shock.

In Figure 34 the heavy lines bound the areas sensibly affected by the Chilian earthquakes of 1822, 1835, 1837, and 1906. The position and elongation of each area suggest that all these disastrous shocks emanated from faults which were long, submarine, and parallel to the coast.

A similar rupture of central California caused severe damage to San Francisco in 1868. The fracture, where the slipping of the crust took place, called the Haywards Fault, crops out on a line north of, and nearly parallel to, the San Andreas Rift (Figure 24, page 49). The Haywards Fault runs along the base of the Berkeley Hills. Across its trace now lies the University of California. If history repeats itself and strong movement be there renewed, the large university stadium is likely to be sliced into two parts.

On March 26, 1872, a heavy shock took place in Owens Valley, California, below Mount Whitney. It was felt from Shasta to San Diego and at points far beyond the border of Mexico. The tall trees of the Yosemite were waved about and "bent like mere twigs" as the seismic waves raced westward. Because of the sparse population, the casualties numbered fewer than 100, but the shock was probably much severer than the one which ruined so much of San Francisco in 1906. The air was charged with dust for a whole day. Owens Lake was jostled into turbulence and long, high, foaming waves. Water fountains reaching 75 feet in height were spurted from the writhing fissures, and many massive landslides occurred. The quake was clearly due to faulting. The displacements are now, 54 years later, clearly marked by low cliffs along a belt 40 miles long. The highest of the fault scarps is 23 feet in height. The accompanying hori-

zontal movements, shown by the offsetting of fences and roads, which were sliced by the fault, were not so pronounced; the maximum was 16 feet. For thousands of years Owens Valley had been the scene of similar faulting, occurring at intervals. Here in 1917, as already noted, was another slight shock, which injured the Los Angeles aqueduct.

On October 2, 1915, a fault, 22 miles long, suddenly devel-

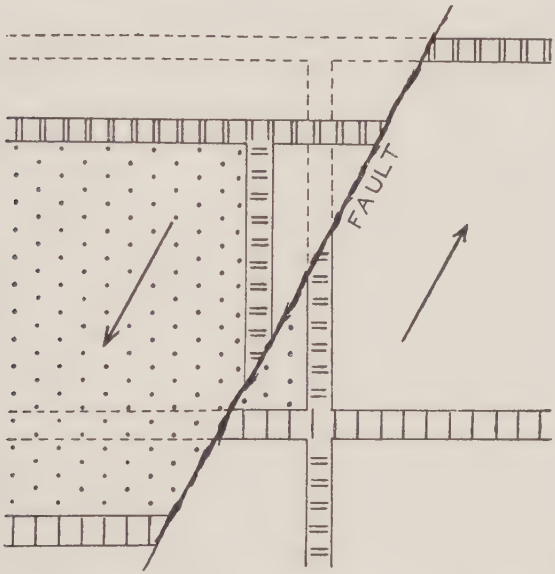


FIG. 35. DISPLACEMENT OF FARM BOUNDARIES ALONG THE JAPANESE RIFT OF 1891. (After Kotô.)

oped in Pleasant Valley, Nevada. The accompanying earthquake was felt from San Diego to Oregon, and from the Pacific coast to Salt Lake City. The fault scarp ranges from 5 to 15 feet in height.

The 1887 earthquake of Sonora, Mexico, was felt over an area of 500,000 square miles; it was caused by a fault 35 miles in length. The dislocation is marked by a chain of fissures and by steep clifflets, which are reported to have a maximum height of 20 feet.

Another heavy Mexican shock, of 1912, was occasioned by

the apparently simultaneous formation of two faults, one 12 miles long, the other 30 miles long. The fault scarps do not surpass a few feet in height.

The colossal shock to Alaska in 1899 is explained by faulting, which was connected with the remarkable uplift of the coast, by amounts reaching as much as 47 feet.

The fault responsible for the Japanese disaster of 1891 is 60 miles long, and is marked by scarps reaching 18 to 20 feet in height. Here again, as already noted, there was horizontal shifting of the ground; this was registered by dislocation of paths, fences, and field divisions. In Figure 35 the broken lines show the positions of field divisions before the earthquake; the solid lines show their present positions.

In 1906 the island of Formosa was shaken badly when a fault, 30 miles long, was suddenly developed. The observed vertical and horizontal displacements of the ground, marked by the offsetting of roads, were six feet and eight feet respectively.

A tremendous earthquake in New Zealand during the year 1855 is attributed to a fault 90 miles long. The same general region had, in 1848, been similarly jarred when a fault 60 miles long was formed.

Special study was given to the faults connected with the Indian earthquake of 1897. Along the sides of one of these fractures, called the Chedrang Fault, the relative vertical displacements were unequal, reaching a maximum of 35 feet.

Near the mouth of the Indus River an earthquake of the year 1819 destroyed many villages. Felt at distances as great as 800 miles, this shock seems to have been caused by faulting along a 50-mile east-west line. The land to the northward snapped up about 10 feet, and that to the south was jerked down about as much. The elevated tract was called by the natives "The Allah Bund," or "Mound of God." The depressed area was speedily converted into a large lake, from the waters of which the fort of Sindree long projected, as a witness to the catastrophe.

Table IX summarizes these various examples of the facts on which the elastic-rebound theory of earthquakes has been based.

Table IX

FAULTS CONNECTED WITH EARTHQUAKES

REGION; DATE	LENGTH OF FAULT (MILES)	MAXIMUM HORIZONTAL DISPLACEMENT (FEET)	MAXIMUM VERTICAL DISPLACEMENT (FEET)
New Zealand, 1848	60	?	?
New Zealand, 1855	90	?	?
Owens Valley, California, 1872	40	16	23
Sonora, Mexico, 1887	35	?	20
Japan, 1891	60	12	20
India, 1897	12	?	35
Alaska, 1899	?	?	47
California, 1906	190+	21	3
Formosa, 1906	30	8	6
Mexico, 1912	30	?	2
Pleasant Valley, Nevada, 1915	22	?	15

The first column of figures gives the lengths of the visible faults in miles. The other two columns give the horizontal and vertical components of movement, so far as known. Each of these master fractures is deep, miles deep, perhaps many miles deep. If we think of that fact and of the thousands of cubic miles of rock suddenly displaced, we begin to understand the enormous energy of an earthquake.

The master fissure at the fault, the *cause* of the earthquake, must be rigorously distinguished from the host of short, irregular cracks which are the *effects* of an earthquake. Such secondary fissures swarm in the ground lacerated by the passage of seismic waves. The burst pavements of San Francisco in 1906 furnished small examples of compression, crushing, and fissuring, by an elastic wave which had travelled many miles from its point of origin. The bursting of the pavements must have caused local tremors, but was itself the product of a distant, infinitely greater displacement.

The fault scarps (Figures 23, 25, 28, and 42) prove changes of level just at the lines of fault. The elastic-rebound theory of earthquakes demands that wide belts of land on each side of the fault trace must have shared in the deleveling. In general the relative uplift or subsidence is at maximum along the fault

trace, and fades out on each side of it. We have noted, too, that the amount of unleveling along the line of the fault itself is variable. Clearly, then, the earth's surface has been warped.

Along the sea-coast the effects of the deleveling leap to the

Photograph from the United States Geological Survey.

FIG. 36. SUDDEN UPLIFT OF THE ALASKAN COAST, 47 FEET, DURING THE EARTHQUAKE OF 1899; TURNER GLACIER IN THE DISTANCE.

eye. Inland the amount of crustal warping can be obtained only by the careful methods of precise leveling.

Measurements were made at a dozen points in India after the 1897 shock. Most of them show uplift of the ground by amounts ranging up to 24 feet. Other bench marks were found to have sunk. There, as in some other recorded cases, the changes of level affected the intervisibility of points on the earth's surface. Proof of this, at the Garo Hills, was specially evident to signalers of the Military Police, who had long been practising with the heliograph at fixed stations in these hills.

The astonishingly rapid uplift of the Alaska coast in 1899 was

47 feet or more. A broad region including mountains, glaciers, and sea bottom suddenly sprang up many feet. See Figures 36 and 37. The photograph shows a beach thus suddenly elevated about 40 feet; the strand line marked by the waves before the displacement is well shown in the mid-ground of the picture.

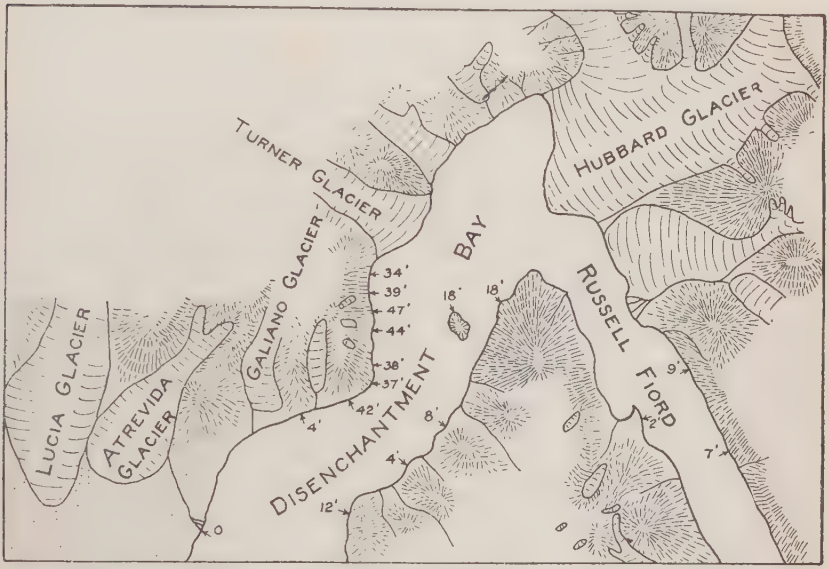


FIG. 37. MAP OF PART OF THE ALASKAN COAST, SHOWING IN FEET DIFFERENT AMOUNTS OF UPLIFT, CONNECTED WITH THE EARTHQUAKE OF 1899; SCALE SIX MILES TO ONE INCH. (After Tarr and Martin.)

Years after the paroxysm, barnacles, or sea acorns, were photographed alongside seedling alders, which could take root only at levels well above those reached by the spray from the ocean waves. Figure 37 is a map of Disenchantment Bay and vicinity, the region of maximum uplift. The movement of the ground was unequal, as indicated by the figures which show its amount in feet. The uplift affected the glacier-covered mountains many miles to the southward of Russell Fiord. On the other hand, the outer part of the adjacent Yakutat foreland and also the sea bottom at and beyond the mouth of Yakutat Bay subsided. It was proved that this sudden, widespread depression of the ground reached a maximum of more than seven feet. The total

deleveling was therefore more than 54 feet. Can one realize the colossal energy involved?

Other celebrated examples of regional uplifts were associated with major earthquakes in South America (1822, 1835, and 1839); in New Zealand (1855); in Japan (1891—elevation of 21 feet).

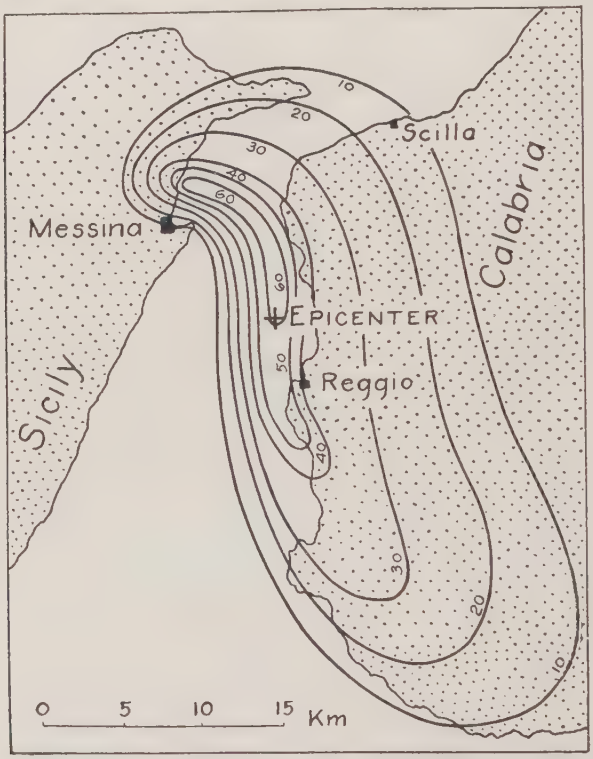


FIG. 38. MAP OF LINES OF EQUAL SUBSIDENCE CONNECTED WITH THE MESSINA EARTHQUAKE OF 1908; LINES AT EQUAL VERTICAL INTERVALS OF 10 CENTIMETERS. (After Sieberg in "Erdbebenkunde," G. Fischer, Jena.)

The elastic-rebound theory as clearly demands that there shall have been crustal movements in the opposite sense; that is, regional subsidence, also connected with earthquakes. We glance at a few examples.

The fearful shock to Messina, in 1908, was accompanied by the sinking of the adjacent coasts of Calabria and Sicily. Figure 38 shows the amount of sinking by lines. For instance, the line

bearing the number 10 joins points where the subsidence was 10 centimeters, or 4 inches. The greatest sinking, near the epicenter and focus of shock in the Strait of Messina, was a little more than 60 centimeters, or about 2 feet. This map represents very delicate and accurate work in the determination of levels.

FIG. 39. PARTIAL DROWNING OF A VILLAGE ON A COASTAL PLAIN OF NEW GUINEA BY SEISMIC SUBSIDENCE, IN THE YEAR 1907.

In 1907 an earthquake in New Guinea was accompanied by subsidence which partly drowned trees and native houses (Figure 39).

In 1751 the coast of San Domingo, through a length of 60 miles, was drowned as it shook violently. During an earthquake of 1762, 60 square miles of the Chittagong district of Bengal sank below the sea. The Causa Nova district of Calabria sank a maximum of 29 feet as an accompaniment of one of its many strong shocks. Very extensive areas of the Mississippi alluvium sank during the prolonged tremblings of 1811–1812. The Japanese have a tradition that the large Biwa Lake, of central Japan, a basin measuring 36 miles by 12 miles, was formed at the time of a first-class earthquake in the year 286 B. C., the famous volcano, Fujiyama, originating at the same time.

A most startling set of changes in and around Sagami Bay took place in connection with the Tokyo-Yokohama disaster of 1923. Figure 40 is a rough sketch of the situation. We note the

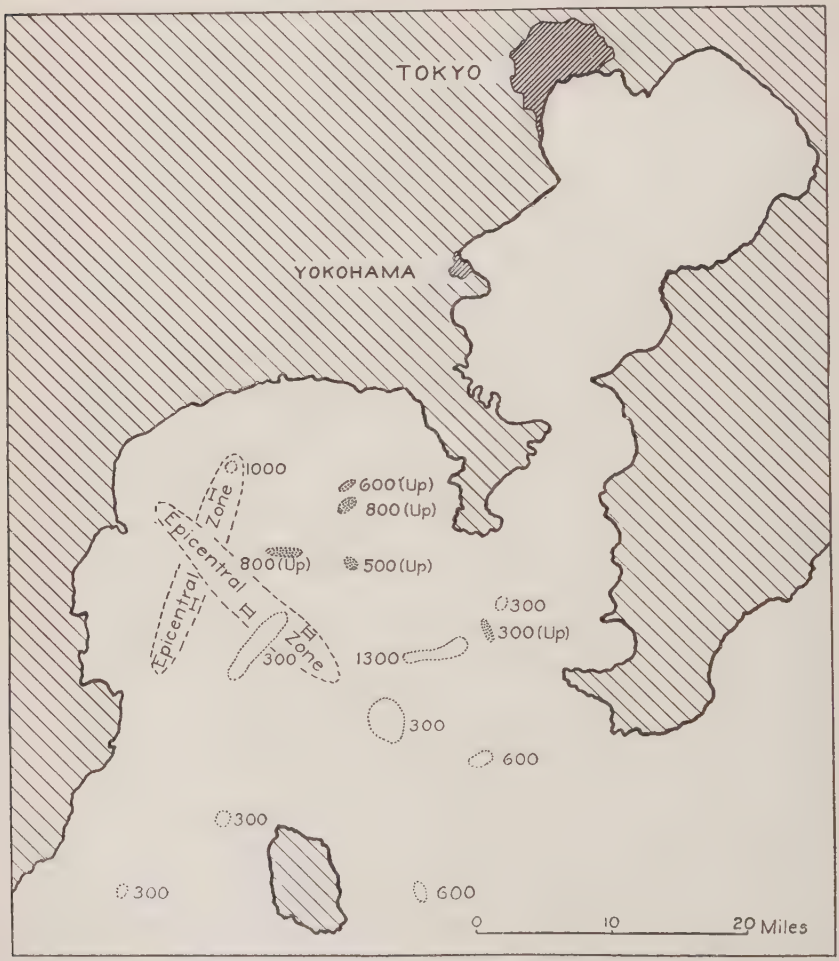


FIG. 40. MAP OF SAGAMI BAY, SHOWING IN FEET APPROXIMATE AMOUNTS OF DELEVELING OF THE SEA BOTTOM, CONNECTED WITH THE TOKYO EARTHQUAKE OF SEPTEMBER 1, 1923. (AFTER SUDA.)

position of Tokyo, Yokohama, and of the two epicentral zones or areas below which the main shocks originated. These foci were beneath Sagami Bay. Fortunately, the bay had been sounded in great detail by the Japanese Hydrographic Office

during the year 1912. In spite of the many calls on the resources of the government, five ships were sent out in January, 1924, to repeat the complete sounding of the bay. In a few weeks many thousands of soundings were made, so that the contour of the sea bottom was determined with much accuracy. This enterprise well illustrates the energy and wise farsightedness of the Japanese in meeting a difficult problem. The resurvey of Sagami Bay is important because of its relation to estimates of future earthquake hazard; its purely scientific value is already quite clear.

A comparison of the two surveys of the sea bottom should, of course, be governed by the fact that each sounding is affected by errors, the chief of which is due to some uncertainty as to the exact position of the sounding vessel when the sounding is made. In the present instance, however, the errors in no case total more than a few per cent of the actual depth of water. According to high authority, none of the soundings in even the deeper parts of the bay gave a depth differing from the true value by more than about 100 feet.

Some of the changes in the depth of the sea bottom may well be due to submarine rock-slides or mud-slides, caused by the earthquake; for the earlier soundings showed the sea floor to be very uneven, with steep slopes. At least one Japanese geologist is inclined to attribute the changes of depth chiefly to such slides of weak material, and clearly the suggestion is worth careful examination. However, most of the authors who have described the changes believe it necessary to assume purely vertical movement of the rocks as the dominant cause. The following brief account of the changes has been compiled from several of the published memoirs. It should be understood that further detailed study of Sagami Bay is needed before certainty can be claimed for the actual amounts of uplift and subsidence.

In Figure 40, five areas of very pronounced shallowing are indicated by closed lines and stippling, these areas being marked "Up." The maximum amount of shallowing is about 800 feet. Interspersed are areas of deepening, which are marked with

lines inclosing unstippled areas. The apparent downward movement of the sea bottom reached a maximum of about 1,300 feet. "In the eastern areas, the north end of a line 1.5 miles long is raised 810 feet, and the south end lowered 1,224 feet. Before the earthquake [that is, in 1912] the sea bottom was inclined at

Photograph by Yamasaki.

FIG. 41. ROCK BENCH AND SEA CLIFF, UPLIFTED DURING THE TOKYO EARTHQUAKE OF SEPTEMBER 1, 1923; AT ENOSHIMA, NEAR KAMAKURA.

an angle of 19 degrees to the north; after the earthquake the slope was reduced to 5 degrees in the same direction."

The total volume of the apparent depressions has been estimated as 50 cubic kilometers, or over 12 cubic miles. The total apparent uplift has been put at 20 cubic kilometers, or 5 cubic miles.

The unleveling of the dry land was much less significant. In maximum the shores of Sagami Bay were uplifted six feet. Figure 41 is a photograph, taken by Mr. N. Yamasaki, showing the elevation of the sea cliff and wave-cut bench of rock at Enoshima, near Kamakura, on the north shore of the bay; the uplift was here between three and four feet.

It is clear that the changes of the dry land in elevation were

sudden and directly connected with the main shock of September 1, 1923. Much less certain is the relation between that shock and the incomparably greater displacements of the sea bottom. If these were equally sudden, we might well expect that enormous sea waves should have been generated, much

Photograph by Fairbanks.

FIG. 42. SAN JACINTO FAULT SCARP AT UPPER END OF BOREGO VALLEY, CALIFORNIA.

higher than those which actually came to the shores immediately after the main shocks. We do know that the submarine displacements occurred within the interval from 1912 to January, 1924. Possibly they were largely accomplished by slow, quiet, plastic deformations of the rocks, which under the bay overlie lava or hot, plastic rock at no great depth. In part the dislocations may have taken place during the prolonged period of after-shocks, following the main earthquake at noon of September 1, 1923. Perhaps with further study the Japanese geologists may yet discover facts throwing light on what happened underground and when it happened. Of special interest would be to determine

the relative importance of rock-sliding in the changes of depth.

Let us now look back into earth history. Even the recent jump of the Alaskan coast was trifling when compared with many ancient faults. By successive small displacements, each of which was doubtless accompanied by earthquakes, the total slipping along a single plane of faulting has, in many an instance, reached several thousands of feet. Some measurements of the displacement or throw have given more than 10,000 feet. The corresponding earthquakes of old days were doubtless numbered by millions. Figure 28 (page 54) is a view of the San Andreas Rift; its steep slope is the integrated result of many old slips of the rocks. In Figure 42 we see the San Jacinto cliff of faulting at the upper end of Borego Valley. The crust block of the foreground has been dropped down, relatively to the mountain block of the background. The San Jacinto Fault is at least 75 miles long. Since the white man came to California, it has been responsible for two severe earthquakes. It may be noted that it runs northwest-southeast along the San Jacinto Range and within striking distance of Los Angeles. This rift is marked by canyons or steep mountain scarps through nearly all of its length, and this new topography is not yet finished, for on April 21, 1918, a slip on the San Jacinto Fault affected the whole of southern California and western Arizona.

Still higher than the San Jacinto scarp are many fault cliffs in Oregon, Nevada, and Utah. In most cases, however, the displacements along those fractures seem to have come to an end, or, if continuing, to be so slight as not to cause heavy shocks to the crust of the earth.

Two tests of the theory of elastic rebound have been applied so far. First, the theory says that earthquakes are generally caused by sudden faulting of the crust. The faults can be seen, mapped, photographed. The shock is greatest along the trace of the fault. Secondly, the theory tells us that broad belts of ground alongside the fault trace should be permanently displaced, up or down or horizontally, according to the play of forces in the earth's crust. We have seen how well this expecta-

tion is realized in several shaken regions. Now we note a third test of the theory.

All central California was being increasingly strained during the decades previous to 1906. The earth's crust was there being compressed horizontally in some places and dilated at other places. Extensive areas were involved in each case. In the compressed areas, therefore, points on the surface were being brought closer together. In the dilated areas points were being pulled apart. Such displacements are logically demanded by the elastic-rebound theory. The exquisitely accurate work of the United States Coast and Geodetic Survey shows that this anticipation from the theory was fulfilled. Some of their triangulation stations were caused to approach each other by distances of several feet. Other pairs of stations, during the same few decades, slowly traveled apart by comparable amounts.

Again, when the 1906 earthquake took place and the crustal strain was relieved, the horizontally compressed areas suddenly expanded because relieved of elastic pressure. Triangulation stations as suddenly moved apart. Similarly, the horizontally dilated areas contracted. Triangulation stations on these parts of the crust suddenly approached each other.

The same thing happened in California when the earthquake of 1868 occurred. Probably at the time "about 1,000 square miles of the earth's crust, comprised between the four stations, Mount Tamalpais, Farallon Lighthouse, Ross Mountain, and Chaparral, were permanently displaced to the northward about 1.6 meters (5.2 feet)," in the direction 11 degrees west of north. The station, Loma Prieta, was permanently displaced about 3 meters (nearly 10 feet) in the direction 53 degrees east of south.

The combined effects of the 1868 and 1906 earthquakes have been to increase the distance between Mount Tamalpais and Black Mountain about 3 meters (10 feet). This is an increase of one part in 26,000.

Not only so. The permanent displacements of all points disturbed during the 1906 earthquake were approximately parallel to the San Andreas Fault, as they should have been according to

the elastic-recoil theory. The total shifts reached 15 feet or more. The displacements on each side of the fault fracture were less, according as the distance of the displaced points from the fault was greater. Near the fault, on the east, the average displacement was 5.1 feet; on the west, 9.7 feet.

Similar changes in the mutual distances of triangulation stations have been proved in Sumatra, as the result of a severe earthquake there in 1892. The resurvey of northern India after the shock of 1897 proved the same kind of crustal behavior in that country.

It is clear that the elastic-rebound theory meets the third of our tests. An ordinary earthquake is the jar to the earth's body, caused when the strained crust suddenly breaks and snaps back or elastically recoils.

We have already seen that the rebound is not quite instantaneous. When an elastic structure, a bridge for example, breaks down, the collapse takes time. Movement may begin along a single short crack, generating fore-shocks. The breaking spreads. The fall of the main mass gives the main shock. Succeeding adjustments of the ruined pile of steel or stone cause weaker after-shocks. The earth's crust behaves in the same way. The fore-shocks of an earthquake are generally not important in number or intensity. After-shocks may number thousands, and they may be severe. The fracture of the crust, causing the main shock, may elsewhere increase the stress to the breaking point. A new fracture suddenly develops at that secondary center, where there is a second great jar to the crust. And so on. The impulse to further fracturing and shaking is telegraphed all around. The persistence of these after-shocks is terrible for the survivors of the main shock; few shelters are safe, for days together. The high nervous tension is prolonged.

The Japanese earthquake of 1923, the one that ruined Tokyo, is held to have been such a relay earthquake. The first break in the crust was inland; it caused but a moderate shock. It was the trigger that set off the main displacements of Sagami Bay, many miles away. Again, from Sagami Bay, the impulse to a third

breaking of the crust was sent through the crust to a point 300 miles from the bay, and under the open Pacific. At this third point, 27 hours after Tokyo was destroyed, there was a shock

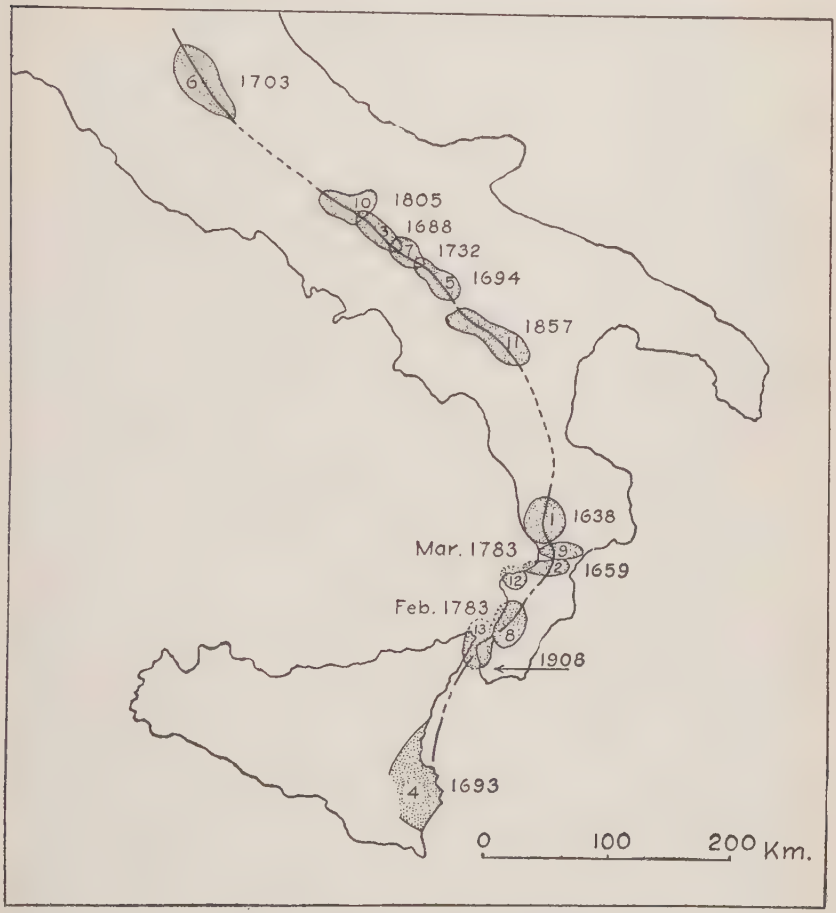


FIG. 43. MIGRATION OF EARTHQUAKE CENTERS IN ITALY. (After Sieberg in "Erdbebenkunde," G. Fischer, Jena.)

which was nearly or quite as heavy as the one responsible for the principal loss of life.

The centers of disturbance along the axis of Italy have wandered up and down between the times of the earthquakes in 1638 and 1908; as shown by Figure 43. On this map the epi-

central tracts, the places of specially strong motion, are marked by the dotted areas; the corresponding dates of the shocks are also given.

We are now prepared to see the essential relation between

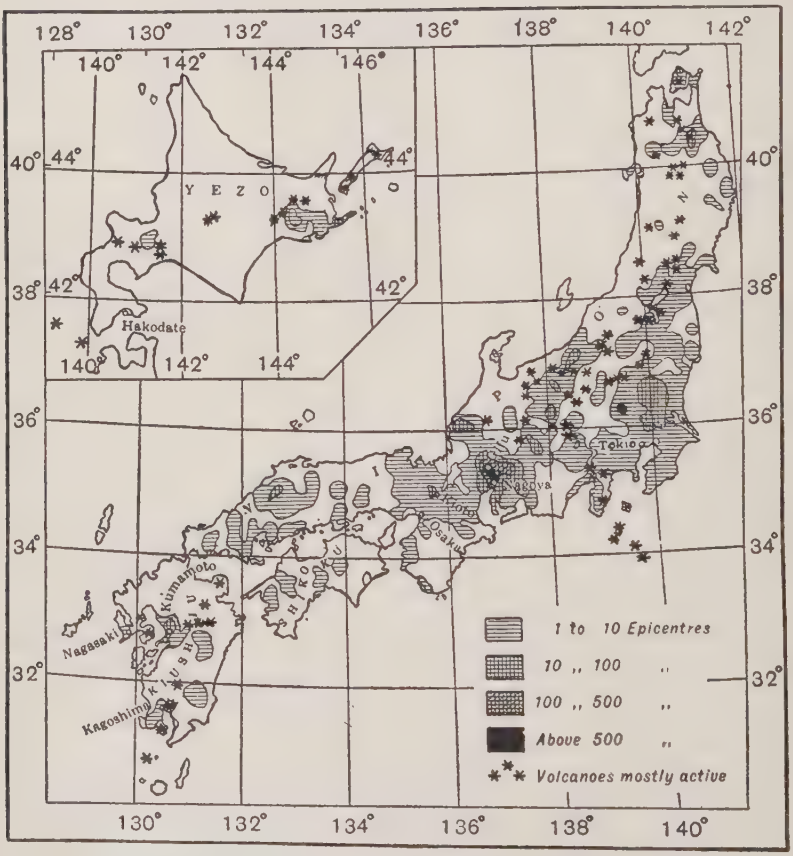


FIG. 44. SEISMIC MAP OF JAPAN, SHOWING LOCATIONS OF ITS PRINCIPAL VOLCANOES. (After Reeds and Davison.)

earthquakes and volcanoes. Where the crust fractures go deep, gas-charged lava may rise to the earth's surface. In fact, volcanoes are best explained as emanations from such abyssal fissures. Very often, therefore, earthquakes and volcanoes are associated both in space and time. But the ordinary earthquake is not the effect of volcanic action. Both quake and volcano are

effects of a common cause, the sudden fracture of a strained crust.

In 1914, southern Japan was shaken, nearly simultaneously, at two points. From them seismic waves spread out. These shocks were caused by breaking of the crust. The fracturing changed the pressure conditions of the lava underlying the volcanic cone of Sakura-jima. The cone, therefore, erupted violently. Here, then, we have the special case of eruption and shock, both developed through the displacement of the solid crust. Both were due to a common cause.

Figure 44 indicates with stars the location of Japanese volcanoes, and with shading the distribution of the seismic centers of many dated earthquakes. The faults are not shown, but they are more numerous than either the centers or the volcanoes.

In all this we are dealing with earthquakes of the kind that causes great destruction. The much feebler shocks, caused by volcanic explosions or by sudden injections of liquid lava into the crust, belong in a quite different category—the class of true volcanic earthquakes.

Finally, the elastic-rebound theory of earthquakes can be tested in a fourth way. If each principal shock is due to sudden fracture and displacement of the earth's crust, then that jar must have occurred at some distance below the surface. The heavy blow or jerk is delivered on a small interface within the crust. Thence elastic waves rush away in all directions. At a moderate distance they are propagated practically as if the energy had all been supplied at a point which, for mathematical convenience, may be regarded as replacing the actual fault plane or interface. This point of origin is called the Focus, Centrum, or Hypocentrum of the earthquake (Figure 45). The point on the surface vertically above the focus is called the Epicenter or Epicentrum. The earth particles endowed with equal energy by the elastic waves are joined by heavy solid lines, each bearing a numeral. These lines at the earth's surface are the isoseismal lines of earthquake maps. Arrows represent the wave rays; that is, lines drawn at right angles to the advancing wave fronts.

One of the first steps in the study of an earthquake is to locate the epicenter. Usually this can be done with at least moderate accuracy. Various methods are employed. If the shock has centered in a well-populated region, the epicenter can be placed approximately by mapping the lines joining all points of

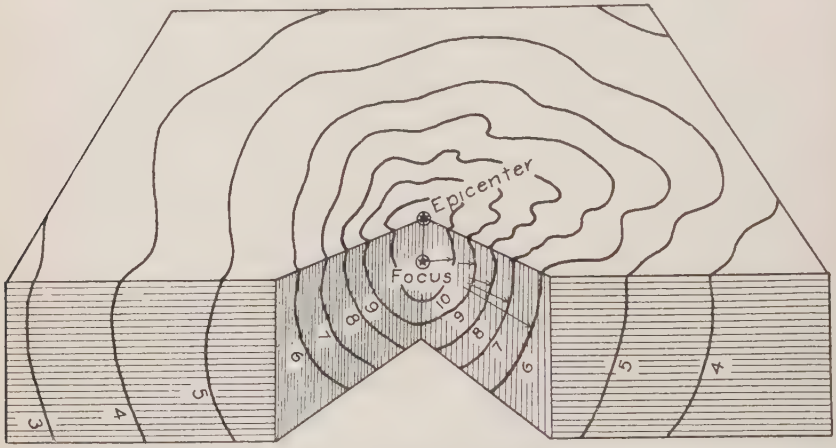


FIG. 45. DIAGRAMMATIC REPRESENTATION OF THE RELATIONS OF SEISMIC FOCUS, EPICENTER, WAVE FRONTS, WAVE PATHS, AND ISOSEISMALS. (After Sieberg in "Erdbebenkunde," G. Fischer, Jena.)

equal seismic intensity—the isoseismal lines. The map of the isoseismals for the Charleston earthquake illustrates the point (Figure 7, page 16).

More satisfactory results are obtained by analyzing the graphic records of the seismographs. This method need not be described on the present occasion. It has the very great advantage of enabling the seismologist to locate epicenters in the ocean basins, far from any observer. For example, we look at a map of epicenters in the western Pacific region (Figure 8, page 17). We locate Australia, Japan, Kamchatka. The dots indicate the epicenters of major shocks recorded by instruments. We note also the concentration of such heavy quakings in and near the ocean deeps, shown on the map by shading.

Having located the epicenter, the next problem is to determine the depth of the focus. This determination is not easy. It was first attempted by Mallet, the father of modern seismology.

Cracks in buildings tend to be formed at right angles to the direction of the seismic impulse. Where the perpendiculars to the cracks intersect is the focus. Mallet's method is inaccurate. Other methods, too technical for description here, are to be preferred. These show that earthquake foci differ as to depth. In general the most trustworthy determinations give depths no greater than 25 miles; their weighted average is not far from half that. It appears, therefore, that down to a few tens of miles the forces can accumulate until the strength of rock is overcome, and rupture with shock takes place. In the next chapter we shall study reasons for believing that the earth's crust is of this order of thickness, though thicker than the earth shell lying above the average seismic focus.

For the present we leave the subject, concluding that actual measurements of the depth of focus are consonant with the elastic-rebound theory of earthquakes, which thus withstands this fourth and last test.

But one may ask: "Suppose the theory to be true; then what about it? What difference can it make to mankind?" Space fails for a full answer to this entirely proper question. I shall note, however, one practical application of the theory.

If earthquakes are due to the straining of the earth, we may be able to watch the progress of the strain and ultimately learn to prophesy where, and perhaps when, the crust will snap. Fairly elaborate plans are already worked out for measuring earth strain, which develops as the years go on. It may take a generation or two to accumulate sufficient data for the purpose of forecasting the place, and less probably the time, of earthquakes, but, if the method should prove successful, neither the delay nor the hard labor of perfecting the method would, in the centuries to come, be significant. Consider the inestimable boon to our race if pure science could make us this princely practical gift!

Having reviewed the effects and causes of earthquakes, we may now turn to take a closer look at the character of seismic

motion. Here again seismology has practical applications. For instance, the builder and engineer should understand the modes of seismic motion if they are to raise structures wisely. Their crafts must become specially crafty in countries like California or Japan or Italy. Yet we can not dwell on this immensely important phase of our subject either. For quite another reason we concentrate attention on the character of seismic motion.

The manner of propagation of earthquake waves tells us much about the physical nature of the earth's interior. This is one of the supreme discoveries of seismology.

First we shall consider some of the naturalistic facts.

Something can at once be learned from the sounds emitted during an earthquake. Since grammar school days we have known something about the nature of sound; in part, seismic waves are no more mysterious than that.

Many earthquakes are heard before they are felt. The common noise is a crescendo growl, reaching maximum loudness almost simultaneously with the maximum shaking of the ground. The quality is like that of the sound of heavily laden carts or of a speeding freight train; or like thunder, more or less distant, swelling to a terrifying roar. Near the epicenter the roar is often punctuated with sharp explosive noises, recalling big guns in action. The sum of the noises may suffice to drown completely the crash of falling buildings close to the observer. All the earth sounds agree in having low pitch. It may be so low that some ear-drums are not sensibly affected, though other persons in the surrounding region can hear the sounds.

The intensity of the sound bears no fixed relation to the strength of the shock to the ground. The sound may be notable though the earthquake is slight. The Anglo-Saxon name for an earthquake was "earth dyne" (earth din), because an outstanding feature of these events in central and western Europe is noise rather than strong motion of the ground.

Modern studies have shown that the sounds are due to the transmission of vibratory energy from the rock to the air. In both mediums the vibrations are transmitted in the form of a

wave of alternating condensation and rarefaction of the material. From the seismic focus, where the blow or jerk was applied, the waves diverge in all directions, after the analogy of the waves in a pond which has been stirred by dropping a pebble. The line drawn at right angles to the advancing wave front we call the wave ray or wave path at the point of intersection. Wherever

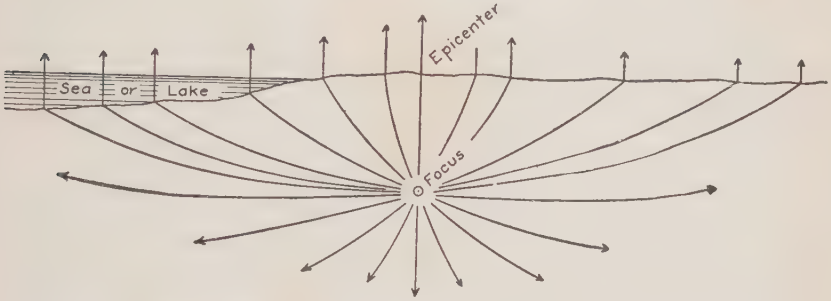


FIG. 46. WAVE PATHS AND THEIR REFRACTION AT THE SURFACE OF THE SOLID ROCK. (AFTER SIEBERG IN "ERDBEBENKUNDE," G. FISCHER, JENA.)

the ray passes from one medium to another of different compressibility and density, the ray is bent at the contact of the two mediums. The contrast of rock and water or air with respect to compressibility is so great that all waves which can pass from the solid ground into either of these fluids are bent into almost vertical paths (Figure 46). This is true, no matter what may have been the original directions of the rays in the rock. Hence on the ocean, earthquake sounds and jars seem to come from directly beneath the observer.

Strongest at the center of shock, the sound spreads outward in all directions, weakening as it travels. Lines joining all points of equal intensity of sound on the surface are called isacoustics. Figure 47 shows the spreading of the sound energy during the Hereford earthquake of 1896; the isacoustic lines bound the successive belts (dotted), which on the map indicate the percentages of the reports containing statements that the sound was heard.

Because sound waves progress through the alternating condensation and rarefaction of air, water, or rock, they belong to the large class called *condensational* waves or waves of compres-

sion. One set of earthquake waves belongs in this class. The medium is compressed and dilated in the direction of the wave path, along the wave path. Hence an alternative name for waves of compression is *longitudinal* waves. The motion of an in-

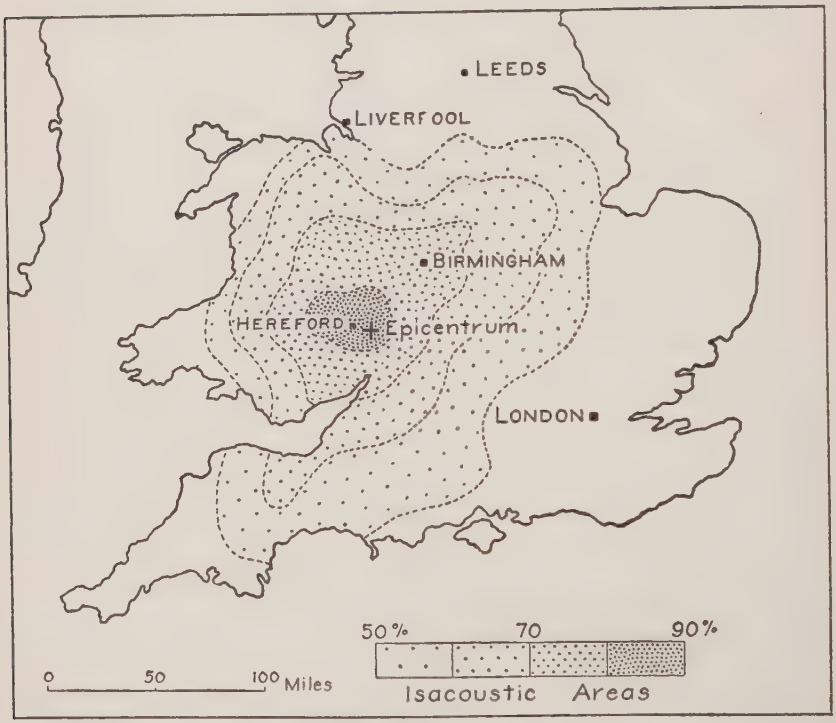


FIG. 47. SPREADING OF THE SOUND OF THE HEREFORD EARTHQUAKE. (After Sieberg and Davison, by Permission of G. Fischer, Publisher.)

dividual particle of the rock may be illustrated by Figure 48. The lower arrows show the wave path for a longitudinal wave. Initially the particle is at the position marked 0. As the particle behind it, that is, to the left, gives up its energy, which was derived from the seismic impulse, our particle is caused to move into the successive positions 1, 2, 3, and 4. At some position, which we assume to be No. 4, the elastic resistance finally stops the forward movement. The particle then snaps back, elastically, through the original position, now No. 8. Momen-

tum carries the particle through positions 9, 10, and 11, to 12. Once more elastic resistance stops the particle. It returns to the original position, 0. The oscillation is now complete. It is repeated until internal friction stops the motion.

Considering now a series of such particles, lined out in the direction of wave motion and equally spaced to start with, we

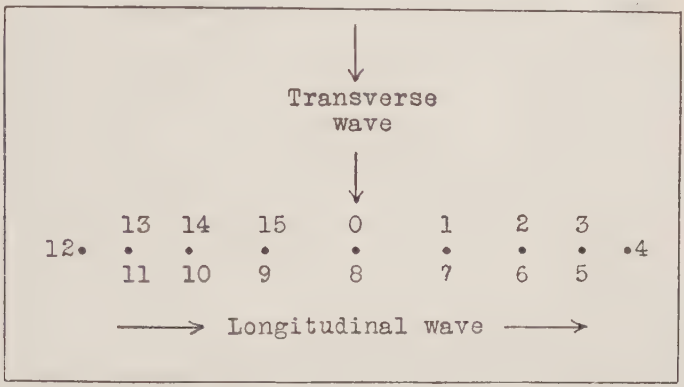


FIG. 48. DIAGRAM OF THE MOTION OF PARTICLES DURING THE PASSAGE OF LONGITUDINAL AND TRANSVERSE WAVES. (After Oldham.)

see that the wave progresses by rhythmical pressing together and pulling apart of the successive pairs of particles—in other words, by alternating condensation and dilatation of the medium.

But when an elastic solid, like glass, steel, granite, or other rock, is struck a blow, another kind of elastic waves is also sent out from the point of impact. Each wave of this second kind progresses through the solid by a different mechanism. Here the particles move at right angles to the wave path. Waves of the second kind are therefore called *transverse* or torsional. The upper, vertical arrows of Figure 48 represent the direction of a transverse wave. The numbered positions of a particle, below those arrows, will illustrate the motion of any particle agitated by a transverse wave.

Longitudinal and transverse waves are, then, the two kinds expected in a solid body, like the earth, after it has just been struck a blow. The importance of distinguishing the two kinds

will be emphasized in the next chapter, when new data concerning the nature of the earth's interior will be described. To prepare the ground for that subject we may also take a glance at the seismograph and the seismogram.

At a relatively short distance from the focus of an earthquake the actual displacement of earth particles by its waves is very small. In order to make those movements more visible, they

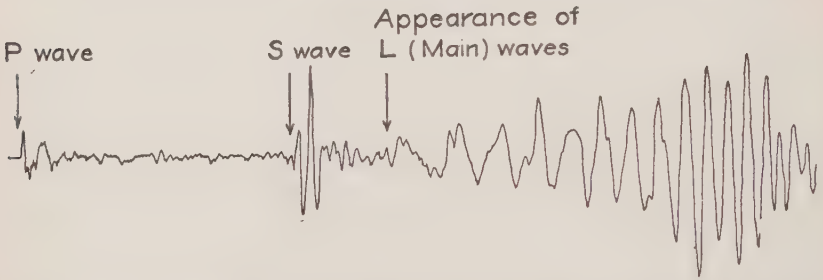


FIG. 49. SEISMOGRAM OF A 1909 EARTHQUAKE, REGISTERED AT PULKOVO, RUSSIA, BY AN INSTRUMENT OF PRINCE GALITZIN: EPICENTER IN ASIA MINOR, 2,300 KILOMETERS DISTANT. (AFTER GUTENBERG IN "DER AUFBAU DER ERDE," BORNTRAEGER, BERLIN, 1925.)

are instrumentally magnified. The magnification is done, and a permanent record of the displacements of the ground is made, by a machine called a seismograph. In principle this is a pendulum which writes down faithfully the story of its own swinging. The bob of the pendulum has inertia. The pier from which it hangs moves instantly as an earthquake wave deforms the ground to which the pier is rigidly attached. The inertia of the bob causes it to lag behind. A long pencil attached to the bob records a tracing on a slowly rotating drum of smoked paper. This record is a seismogram. Other designs employ a horizontal pendulum; the principle of recording remains the same. The horizontal pendulum is hung so that it swings much as a door does on its hinges.

A typical seismogram is a complex curve, but it shows the trace of two impulses. One is at the very beginning of the earthquake disturbance at the station. The other impulse arrives after an interval of seconds or minutes, depending on the dis-

tance of the focus. During the time between the arrivals of the two impulses, the needle of the seismograph traces a series of small vibrations. These are called the First Preliminary Tremors, or *P* (*Primæ*) waves. Somewhat stronger tremors follow immediately on the second impulse; they are called the Second

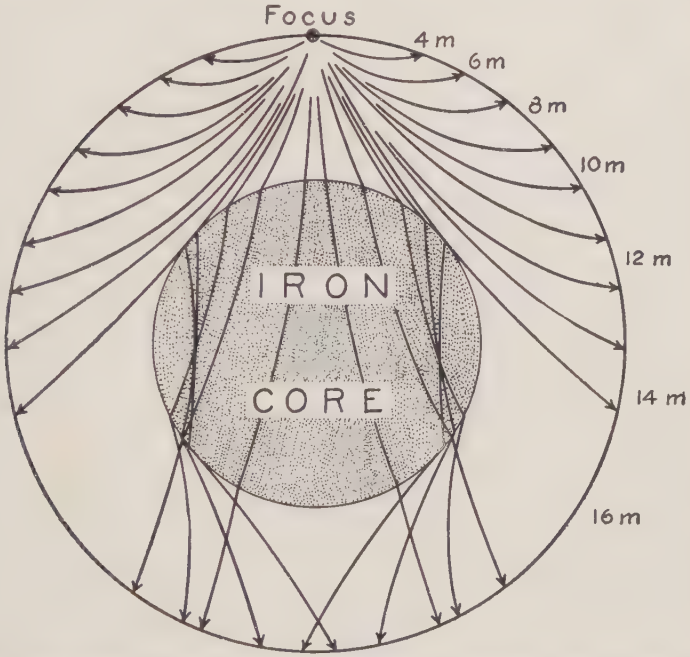


FIG. 50. SECTION THROUGH THE CENTER OF THE EARTH, SHOWING THE PATHS OF EARTHQUAKE WAVES, THEIR REFRACTIONS AND REFLECTIONS, AND SOME OF THEIR TIMES OF ARRIVAL, IN MINUTES AT POINTS ON THE EARTH'S SURFACE. (After Sieberg and Gutenberg, in Sieberg's "Erdbebenkunde," G. Fischer, Jena.)

Preliminary Set of Tremors, or *S* (*Secundæ*) waves. After a time the needle swings much more violently, and a long series of more powerful vibrations, the Main or *M* waves, is then registered.

Figure 49 gives an illustration. It is a tracing from one of Prince Galitzin's seismograms, recorded at Pulkovo, Russia, when, on February 9, 1909, the waves arrived from the focus of a shock in Asia Minor, 2,300 kilometers distant. It will be noted that the displacements caused by the main waves are greater than those caused by the preliminary waves; also that the swing-

ing is more leisurely in the case of the main waves. These have longer periods; hence the alternative symbol *L* for them.

Now, one of the greatest advances of earth physics was made when Milne, Knott, and Oldham, of Great Britain, and Wiechert, of Germany, suggested that the *P* and *S* waves represent longitudinal and transverse waves, respectively. They further suggested that these waves are sent *through* the earth's body from focus to station and do not follow the surface or crust of the earth. Again we use a diagram to illustrate (Figure 50). The earthquake blow was struck at the point marked "Focus." From the focus the elastic waves, *P* and *S*, emanate. Their paths are curved by refraction, because the earth is not homogeneous. Some waves (not shown in the drawing) are reflected at the surface back into the earth. Others are refracted and reflected at the surface of the earth's iron core, of which we shall learn something in the next chapter. Some times of transmission of the *P* waves are indicated in minutes, *m*.

The main waves have quite different paths. The first of these travel along the surface shell of the earth and are recorded at the station. Later on, a second set of main waves reaches the station, having gone round the earth the other way, through the points antipodal to focus and station. If the energy of the shock is very great, these waves may round the earth once more in each case and each time leave their written record at the station.

What we get out of seismograms, at first sight so dry-looking, so technical, will be suggested in the next chapter.

Summary

We have traced earthquakes to their proximate causes. Special stress has been laid on the cause of the more destructive world-shaking blows. We have found volcanic earthquakes to be relatively feeble affairs, probably not much ahead of a big city in their murder rate. Tectonic earthquakes, those due to faulting, are incomparably more serious. Their menace almost begins to rival that of the automobile. After all, we are only one step back. We naturally inquire why the earth's crust is faulted.

That second link in the chain of causation is the problem of a later chapter.

Then we briefly reviewed the character of earthquake motion and the method of recording the motion.

Both phases of seismology have important applications. The discovery of the cause of earth-shaking encourages hope of man's partial conquest over his enemy through a warning forecast of each inevitable shock. The study of seismic motions has already given priceless information concerning the spacious invisible interior of our planet.

CHAPTER III

THE EARTH'S INTERIOR

WHY is North America? Why is there any dry land at all? Man is a dry-land animal; then how comes it that man can exist? The continents would be covered with two miles of sea water, if something did not hold them up. What is that something?

Not long ago, in a geological sense, the flat plain from New Jersey to Florida was under the sea. At that time the ocean surf broke directly on the Old Appalachian Mountains. Previously the southeastern part of the mountain structure had sunk below the sea and became covered with a layer of sand and mud, thickening seaward. The wedge-like mass of marine sediments was then uplifted and cut into by rivers, giving the Atlantic Coastal Plain of the United States. Why was it uplifted?

To the westward are the Appalachians. The geologist tells us of the stressful times when a belt of rocks, extending from Alabama to Newfoundland, was jammed, crumpled, thrust together, to make this mountain system. Why? How was it done?

In former times the sea flooded the region of the Great Plains from Mexico to Alaska, and then withdrew. Why this change?

Accompanied by a geologist, we cross the continent. The geologist tells us of the romantic birth of the Cordillera, stretching from the Front Ranges of the Rockies, across the remarkable mountain blocks of the Great Basin and across the Sierra Nevada and the Great Valley, to the Coast Range of California. Again the mystery of mountain-making clamors for solution.

A long run over the Pacific gives time to frame other questions. Why is it so deep? Why so old? The geologist tells us it is a primitive feature of the globe, unlike the much younger Atlantic basin.

We land on Hawaii, the world's greatest volcano. How was that 30,000-foot cone built from the floor of the deep sea? How is its formidable weight supported?

And then we cross Eurasia. This premier of earth's plateaus stands three miles or more above the general bottom level of the Pacific. Why? The majestic heights of Tibet, Himalaya, Thian Shan, Caucasus, Alps; the Mediterranean; the Atlantic itself—all these busy the geologist and us with questions. Why all these marvels of topography?

Our ship nears home. At the captain's dinner the geologist takes us further into his confidence. He confesses to more wonder than knowledge about these things, but he is sure of one fact: the explanation of mountain, volcano, plain, basin, continent, and ocean is in the interior of our globe, partly in the deep interior. Definite knowledge about the earth is little more than skin-deep. However, it is the invisible stuff of the interior which must be understood before we can hope to answer fundamental questions like the foregoing. Let us now, therefore, examine the facts already discovered concerning the inaccessible depths of the globe. The present chapter is devoted to a description of the solid materials which constitute the earth.

We first study the composition of the skin or crust, most of which belongs to the invisible interior, because, as we shall see, the crust is about 40 miles thick. The geologists infer that composition from observations at the surface. Next, we shall define the three principal classes of rocks in the earth's crust. The crust is not of uniform composition, and this fact determines the existence of continents. They project above the ocean floor because they are made of rocks lighter than the rocks beneath the deep sea. Hence the continents are, as it were, floating on the rest of the earth's body, as icebergs float in water. This buoyant support means stability, permanency, for the plateau-like continents. We shall also find that the mountains, projecting above the average level of the continental surface itself, are also supported by flotation; for under the mountains there is a still greater proportion of light rocks.

Extending our thought deeper into the earth's interior, we shall pay special attention to the density, or relative heaviness, of the matter below the visible crust, because on the arrangement of densities depends the degree of stability of the earth. The interior is stratified or composed of concentric shells. Except near the surface, the density of each shell is less than the density of the shell just beneath it. In general, then, the earth is in a stable condition, with no tendency for any very thick outer shell to sink, because denser than the underlying material. The earth is thus unlike the sun, where such convective overturn is incessant.

However, the conditions close to the earth's surface are different. Just beneath the crust, everywhere, is a comparatively thin shell of material, called the "substratum." This layer is a kind of glass at high temperature, and the discussion of the substratum will involve a summary of the facts known about the earth's internal temperatures. Because this layer is hot glass, it is a very weak substance. Moreover, its density is such that, if a block of the cool rocky crust should become immersed in the substratum, that block would founder or sink to a moderate depth in the substratum.

The difference of density between crust and substratum implies, therefore, potential instability for the earth's crust. That the crust as a whole does not actually founder is due to its strength, and to the fact that its immersion in the substratum, over broad areas, is impossible. When, therefore, we speak of the continents as "floating," we mean that they are supported by the weight of the denser suboceanic crust, the pressure of which is transmitted through the weak substratum.

We shall consider the facts indicating the actual thickness of the earth's crust, specially noting the thickness of the light rocks which underlie the continental surfaces. Finally, certain properties of the substratum will be emphasized, since an understanding of these properties is essential to the argument of the rest of this book.

We begin with the question: How does the geologist proceed

when he gathers the facts leading to inference as to the character of the rocks underlying the land surfaces? Whatever else he does, he seeks those places where Nature has provided open, accessible sections of the earth's crust. The outer skin of the earth

FIG. 51. CANYON CUT IN OLD GRANITE BY THE ORANGE RIVER, SOUTH AFRICA, AT THE "HUNDRED FALLS."

has been penetrated at the canyons cut by running water (Figure 51; Figure 154, page 245). In dry climates the rasping wind also excavates the solid rock, so that deep layers have become visible. Sea cliffs, cut by the horizontal saw of the ocean waves, are other excellent places where may be seen the edges of the

rocky masses that compose the underground (Figures 53, 62, 110–111, 137, and 155, pages 96, 119, 177–178, 220, and 246). Still other natural sections in the earth's crust have been made by faulting; that is, by fracturing and dislocation of the rocks

Photograph by D. W. Johnson.

FIG. 52. HURRICANE FAULT SCARP, UTAH.

that border each fracture. An example is given in Figure 52, a view of a high fault cliff in Utah.

By studying such outcrops, the geologist is able to deduce the nature of the rocks constituting the continents, down to the depth of a few miles. The average density of these rocks is close to 2.70; that is, on the average, they weigh 2.70 times as much as an equal volume of water. This is nearly the density of typical granite, and in fact the principal continental rock *is* granite. Figure 51 is a photograph of the Orange River canyon, sunk in the old granite which forms most of the basement of South Africa, and indeed of all Africa.

We shall do well to pause and glance at the classification of all the different kinds of rocks constituting the continental plateaus.

The most voluminous of all are the so-called igneous rocks.

Granite itself is an example. Each mass of granite was once molten. At that time it was so hot that no crystals could form; it was a glass, a hot, highly viscous liquid. The glass cooled; crystals began to form and to interlock with each other. Finally the whole became converted into a mass of interlocking crystals, which was so firmly knit together that the weak, hot, glassy liquid was all converted into a strong, cold, crystalline rock.

At many different times and places, the prevailing granitic terrane of the continents has been fissured, and masses of other kinds of molten rock, soon solidified, have been thrust into, and out over, the granite, which, however, has always dominated in volume. One of the invading lavas, now frozen into dark-colored solid rock, is pictured in Figure 75, page 138.

These so-called igneous rocks become better understood when studied in the form of thin sections, slices so thin that they are transparent. Such slices can be viewed with a microscope. The constituents of the rocks are thus magnified.

When suddenly cooled, a lava forms a more or less homogeneous glass, which, whatever its color in large masses, tends to be nearly or quite colorless when sliced very thin.

When the lava has not been cooled so rapidly, crystals become conspicuous in the melt. The streaky material between the crystals is glass, which, while very viscous, is often seen to have been pulled out into the irregular streaks by the tumultuous movement of the lava as it flowed.

When still more slowly cooled, basalt, the commonest of all lavas, is like granite in crystallizing completely. The crystals interlock in a wonderful way. Each is mortised into its neighbors. Similarly, most of the other igneous rocks are strong, firm bodies. They can be crushed or torn apart only if great force is used. Natural glass, like artificial glass, is also rigid and strong at ordinary temperatures; it is a fluid at high temperatures and at low pressures. Uncrystallized hot rock, therefore, flows under its own weight. Glassy lavas may run down hill faster than a man can run, though fortunately such speed is exceptional.

We now turn to the second class of continental rocks. Dur-

ing the ages, the igneous rocks have been weathered and washed by the rains. Their detritus has been sorted and deposited as superficial pellicles or lenses of sediment on the granitic foundation. These beds or strata have been gradually hardened into layered sedimentary rocks. Figure 53 gives an illustration of a

Photograph from the Scottish Geological Survey.

FIG. 53. FLAT-LYING STRATA OF THE SEA CLIFFS, ABOUT THREE MILES SOUTH OF WICK, CAITHNESS, SCOTLAND.

series of sedimentary rocks; it is a picture of a series of mudstones and sandstones at a sea cliff south of Wick, Scotland.

The third class of rocks is given the name "metamorphic." Under conditions of elevated temperature and pressure, igneous and sedimentary rocks have been profoundly altered by the formation of new crystalline compounds. In other words, these rocks have been recrystallized. The process of change is called metamorphism, and the resulting rocks are called metamorphic. The prevailing granite of the continents has been more or less subject to metamorphism. When the process has gone to the

limit, the granite has become banded. In that altered condition the granitic rock is given the technical name "gneiss." Figure 54 is a photograph of such banded gneiss. The bands are seen to be nearly straight in cross-section, but commonly they are greatly crumpled. In fact, one of the causes for the metamorphism of

Photograph from the Scottish Geological Survey.

FIG. 54. BANDED GNEISS OF THE OLDEST SERIES OF ROCKS IN SCOTLAND: A LEDGE IN INVERNESS-SHIRE.

granite is crumpling pressure of the kind ruling in the formation of mountain chains.

Having reviewed the three kinds of rocks in the continental plateaus, and having learned that the dominant rock is there granite or its metamorphic equivalent, we now note a strong contrast with the oceanic regions. The deep-sea islands are chiefly made of basalt, a rock with the density of about 3.0, and therefore heavier than granite. Most of these islands are volcanic, and many of them have witnessed violent explosions. Numerous fragments of rocks, exploded out from considerable depths, have been found. Nearly all of the solid fragments are

crystallized basalt or derivatives of basalt; fragments of rocks characteristic of the continents are usually conspicuous for their absence. Particularly, not a cubic inch of granitic rock has ever been found in the hundreds of volcanic islands which dot the region of the central Pacific, one fourth of the area of the whole

Photograph by Arnold Heim.

FIG. 55. BASALTIC FLOW ON THE FLOOR OF KILAUEA SINK, HAWAII. THE CLIFF OF THE BACKGROUND EXHIBITS THE EDGES OF MANY SIMILAR, OLDER FLOWS.

globe. So far as they go, these facts suggest that the suboceanic crust is composed of rocks decidedly different from the rocks constituting the continents.

Figure 55 is a view of a Hawaiian flow of basalt, the typical dominating rock of the deep-sea islands.

The assumption that continental rocks are actually absent, or else very subordinate, in the regions of the open ocean is strongly supported by another fact. Above the average level of the sea bottom are about 2.3 miles of salt water, with a density of nearly 1.03, the density of fresh water being 1.0 exactly. The

same level continues under the continents, and above it is a layer of rock nearly three miles thick, and with a density that is 2.7 times that of fresh water. If the density of the rocks beneath the oceans, from the sea bottom down and level for level, were identical with the density of the rocks beneath the continental surfaces, then the continents would represent excess of matter at the earth's surface. The gravitational attraction of each of these great masses of excess matter would pull up the sea water on the continents. The sea-level would be constantly distorted from the spheroidal form which it must have on a rotating, homogeneous earth. But geodetic and other methods show that the sea-level is not so distorted by anything like the amount expected on the hypothesis. On the contrary, the form of the sea-level is almost identical with the form it would have if there were no continents. In other words, the rocks below the oceans are heavier, volume for volume, than the continental rocks. This contrast exists to the depth of 40 miles or more. The higher density of the suboceanic rocks gives them greater attractive power. So strong is this effect that the gravitational pull of the continents is almost perfectly balanced. The sea-level is, therefore, close to an ideal spheroid of rotation.

At the depth of 40 miles, or one per cent of the earth's radius, the combined weight of the ocean and the suboceanic rock is almost exactly equal to the weight of the continental rock at the same level. The continents are thus kept essentially in flotation and tend to be stable. Continents are high because they float high, just as icebergs project high above the sea.

This condition of balance is called isostasy. The great reliefs of the globe are said to be isostatically compensated; that is, the high parts of the earth's skin are made of relatively light rocks, and the low parts are made of heavy rocks.

Now it is found that if, to the depth of about 30 miles, the suboceanic rock has nearly the density of crystallized basalt, which averages 2.9 to 3.0, or seven to ten per cent more than the density of the continental granite, the balanced condition of the earth's skin can be largely explained.

Further, basalt dominates among the lavas now being erupted, on the continents as well as on the floors of the oceans. This and other facts familiar to geologists tend to show that the crystallized, basaltic earth shell below each ocean basin and, as well, each of the high-floating continents are underlain by a deep, continuous layer of non-crystallized, glassy, eruptible basalt.

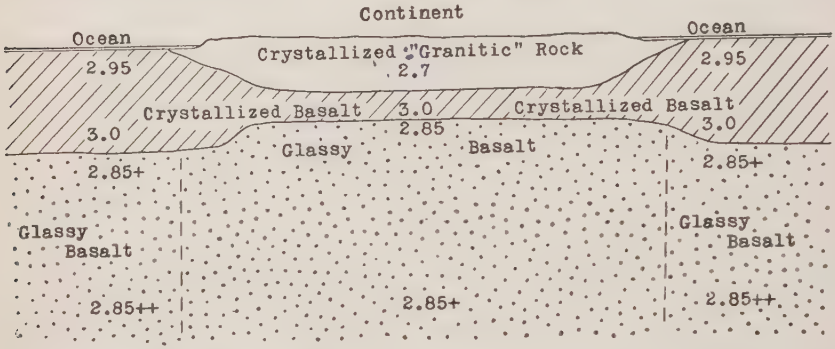


FIG. 56. DIAGRAMMATIC SECTION SHOWING DISTRIBUTION OF DENSITIES IN THE EARTH'S CRUST AND BELOW IT. THE DENSITY GIVEN FOR THE CONTINENT IS THAT OF ITS UPPER PART ONLY.

This layer is a complete earth shell which at a given level is everywhere almost perfectly uniform in composition, though the shell grows slightly denser with each 10-mile increase of depth. For convenience this potentially eruptible layer of basalt will be called the *substratum*, as it is a world-circling shell, underlying the manifestly crystallized, non-eruptible skin of the globe. The earth's skin of strong, solid rocks is fittingly described by the old, popular name "crust."

The density relations of the crust may now be reviewed with the aid of a diagram, a vertical section through the crust and upper part of the substratum (Figure 56). The position of continent and ocean is indicated. The continent stands high because its density, 2.7, at and near the surface is relatively small. Beneath its light, dominantly granitic rocks is a layer of crystallized basalt. This latter is substratum material which has solidified through geological time. Under the ocean is similar basaltic rock, but considerably thicker; because of compression under

its own weight, the density of the rock increases downward from about 2.95 to 3.0. The crust is a little thinner under the surface of the continent, because granitic rock contains more radioactive minerals than basalt. Radioactivity means the steady evolution of heat. Hence it is probable that the crust under the continental surface cools and thickens less rapidly than the suboceanic part of the crust.

Beneath the crust as a whole is the glassy substratum, still too hot to crystallize. Its density increases downward, from about 2.85, but quite slowly. The increase of density because of compression is slightly greater under the thicker suboceanic crust; hence two plus marks are added to the figure 2.85, while under the continent only one plus mark is added.

Still farther down in the substratum, perhaps at the depth of 100–150 miles, the density has increased to 3.0. A little below that depth is the level below which immersed crust-blocks would not sink. From that level downward the density increases all the way to the earth's center.

Thus, under continents and oceans, we have a vertical distribution of densities from the rock surface downward, approximately as shown in Table X, which for convenience includes also data from Table XII, page 109.

TABLE X

	DENSITY	
	CONTINENTAL SECTOR	SUBOCEANIC SECTOR
Surface	2.7	2.95
Bottom of crust	3.0	3.0
Top of substratum	2.85	2.85 +
Depth of 100–150 miles	3.0	3.0
Depth of 1,000 miles	4.5	4.5
Depth of 1,800 miles	9.0	9.0
Center of earth	11.6	11.6

The varied composition of the crust is apparent not only by the average projection of the continents, but also by the specially great projection of many mountain ranges and associated plateaus. By the same methods that are used to test the isostasy of the

continents, these highland regions have been found to represent special concentrations of the lighter rocks. The high mountain masses and high plateaus are also supported almost wholly by flotation. Their surfaces must be underlain by rocks somewhat less dense than the average rock of the continents.

The diagrammatic section (Figure 57) represents this fact. Mountain ranges are chiefly formed of extra-light sedimentary

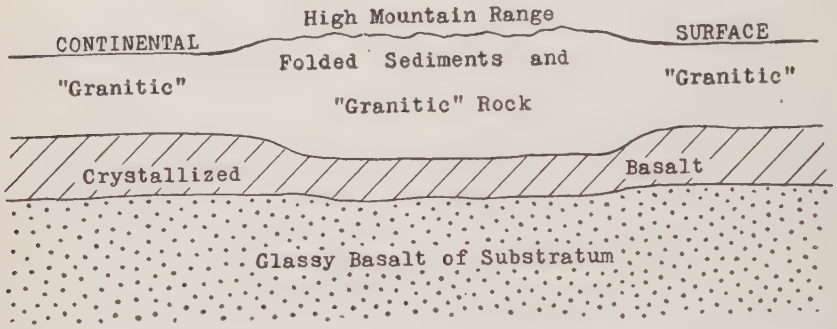


FIG. 57. DIAGRAMMATIC SECTION ILLUSTRATING THE FACT THAT EACH MOUNTAIN RANGE HAS A "ROOT" OF RELATIVELY LIGHT ROCK, INSURING THE STABILITY OF THE HIGHLAND MASS BECAUSE IN FLOTATION ON THE EARTH'S BODY.

rocks, folded and rafted together, so that they, together with the underlying "granitic" rock, represent a specially great thickness of light material. Hence the mountain ranges float high, even higher than the continents. In consequence of mountain-building, some of the crystallized basalt beneath is ultimately remelted to glass; hence this layer of solid basalt is shown as somewhat thinner under the mountain range than elsewhere.

We extend our inquiry still deeper into the earth. Before resuming the account of the basaltic substratum, which is of supreme importance in nearly all our thinking about the mobility of the solid earth, we shall sketch the general nature of the deep interior of the globe.

In the first place, the earth's internal density, below the crust, clearly increases with increase of depth. That fact is proved by several different kinds of evidence.

First, evidence from the earth's mean density. This has been measured by a half-dozen methods. The best value is 5.52, water having the density of 1.0. Since the average density of the crust is close to 2.9, the density of the interior must be much higher.

Secondly, we can find out something relevant from the shape of the earth, especially the shape of the sea-level. The figure of the planet is determined by gravitation and by rotation. We all learned in school that our globe is "flattened at the poles, bulged at the equator." Because it rotates, it is not and can not be a perfect sphere, the shape to which the self-gravitation of any mass of matter tends to reduce that mass. The earth is an oblate spheroid. The north-south, or meridian, section through the globe is, therefore, not a circle, but an ellipse. The amount of the departure from the circular form is called the ellipticity. The principle is illustrated by Figure 58, where *CP* equals *CR*. *RQ* represents the equatorial bulge.

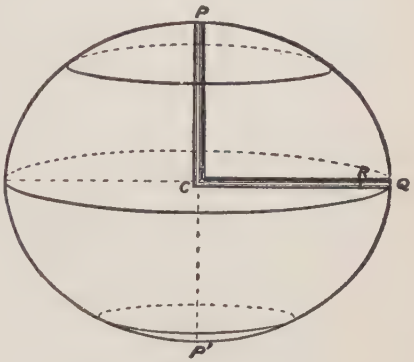


FIG. 58. DIAGRAM ILLUSTRATING THE ELLIPTICITY OF THE EARTH. (From Moulton's "Introduction to Astronomy," The Macmillan Company.)

Now calculations show about one half of the earth's ellipticity to be due to the rotation; the other half of the ellipticity to be due to the gravitational attraction of the bulged-out materials of the earth. These materials must be so arranged that the density of a thick surface layer is much less than the mean density. Otherwise the ellipticity, or equatorial bulging, of the sea-level figure of the earth would be greater than that actually observed. Necessarily, the central density must be greater than 5.52. How much greater is a question still to be solved.

Thirdly, the astronomical change called the precession of the equinoxes also demands the assumption of an increase of

density with depth. The earth has what is called a precessional constant, which itself depends on another quantity, called the earth's moment of inertia. The latter quantity determines a certain irregularity in the moon's motion around the earth. The moment of inertia, thus astronomically measured, proves that the planet can not be homogeneous, but must be composed of shells, the density of which in general increases from the surface to the core.

Fourthly, the assumption of increase of density with increasing depth is an unescapable consequence of the best theory of the solar system. This is the tidal-disruption theory of its origin, first announced by Chamberlin, the geologist, and modified by the physicists, Jeans and Jeffreys. According to the theory thus modified, the earth was once fluid. When fluid, much of its denser material must have sunk toward the center; much of the less dense material must have risen toward the surface. The increase of density with depth, because of intrinsic or chemical differences of the earth shells, would, therefore, have been early established and kept permanent.

A fifth argument. Every known substance is compressible. The sea-level pressure at the earth's surface is the weight of the atmosphere, on the average about 14.7 pounds to the square inch. The pressure increases with depth, so that at the earth's center it amounts to the inconceivable 45,000,000 pounds, or about 22,000 tons, to the square inch. Evidently, such pressures cause rise of density with depth, even if the original material of the earth were intrinsically or chemically uniform.

In order to get a more definite idea as to how important compression is in accounting for the earth's internal density, we shall make the quite arbitrary assumption that the earth's material would be homogeneous if it were all at zero pressure. Let us assume this to be true for all the earth shells to the depth of one half the radius. To that depth the compressibilities of the shells can be rather closely calculated from the speeds of propagation of earthquake waves through the globe. Figure 50, page 87, shows diagrammatically the paths of waves from an

earthquake focus. All paths, except that vertically under the focus, are curved, because the earth is actually heterogeneous and the waves are refracted.

Now, from the times taken for shocks to travel thus on curved paths through the body of the earth, it is possible to determine the speeds of propagation at successive depths. From these speeds we can calculate the compressibility of the successive layers of the earth. In the last chapter we saw that the waves are of two kinds: the longitudinal or P waves and the transverse or S waves. At any point in the earth, the transverse waves travel with a velocity such that its square $(V_s)^2$ is equal to the rigidity (R) of the material, divided by its density (D). Thus:

$$(V_s)^2 = \frac{R}{D} \qquad (1)$$

The corresponding longitudinal waves travel with a velocity whose square $(V_p)^2$ is equal to K, the reciprocal of the compressibility of the material, plus $4/3$ of the rigidity (R), this sum being divided by the density (D). We have

$$(V_p)^2 = \frac{K + 4/3\, R}{D} \qquad (2)$$

Though we do not know the density at a given deep level exactly, yet from the earth's moment of inertia we can estimate within rather narrow limits what that density must be. The famous Laplace framed a mathematical law which can not be very far from the truth. That law gives the approximate value of D in the first equation. We know the value of V_s. It is a matter of simple arithmetic to determine the value of the rigidity from the first equation. Then, in the second equation, we know the value of V_p from the seismograms. We have just found the approximate values of R and D. Hence it is easy to compute the value of K to the same order of approximation. The fraction $1/K$ is the compressibility of the material at the given depth.

Let us now assume the material down to the depth of 2,000 miles in the earth to be chemically homogeneous, with an initial

density of 3.0; that is, the density it would have if it bore no weight at all. The compression of such material under its own weight would give it the densities, at 500-mile intervals, shown in the middle column of figures in Table XI.

Table XI

EFFECT OF PRESSURE ON DENSITY AT DIFFERENT DEPTHS IN THE EARTH

DEPTH (MILES)	DENSITY	
0 (surface)	3.0	2.7
500	3.6	3.2+
1,000	4.0	3.6
1,500	4.4	4.0—
2,000	4.8	4.3+

If we assume the material to have the density of granite at zero pressure, namely 2.7, we get the internal densities, due merely to compression, as shown in the right-hand column of the table.

Clearly, the compression of the earth under its self-gravitation, under its own weight, is a very important cause for the high mean density of the globe, as well as for the deduced increase of density with depth. More than half of the rate of increase is to be explained by the earth's compressibility.

Sixthly and finally, a strong hint that the rest of the increase in density with depth is due to a definite chemical change in the material is given by the meteorites. Thousands of these stones have fallen to the ground and are now preserved in museums. At least in kind, they seem to be fragments of the same world-stuff from which planets are made. Many are largely composed of metallic iron. Some are entirely, or almost entirely, free from metallic iron and are composed of silicates; that is, compounds of silica. Silica itself crystallizes as the familiar quartz or rock-crystal. Its compounds make up most of the common rocks.

Some meteorites are made of a mass of silicate crystals, through which nodules of iron are sprinkled. Such meteorites have been called ferrospors. Still others, lithospors, are made of

a mass of metallic iron, through which crystals of silicate are sprinkled. In Figure 59 are diagrammatic sections of a lithospor (on the left) and a ferrospor (on the right). The solid black is iron; the white areas represent silicates.

The mystery of the high density of the earth and also the chemical nature of the earth is largely dispelled, if we assume that meteorites are really chemical samples of the material out

FIG. 59. DIAGRAMS ILLUSTRATING A LITHOSPOR (LEFT) AND A FERROSPOR (RIGHT). (After Adams and Washington.)

of which much of our globe was made. This is now the prevailing view of astronomers, geologists, and the masters in earth-physics.

According to the recent results of specialists on the subject, the best theory of the earth should include these postulates:

1. The earth's core, in volume about one-sixth of the whole planet, is composed of metallic iron, alloyed with a small proportion of nickel and other metals, which appear in iron meteorites. In Figure 60 the core is shown by stippling. At the center the density approaches 11.6, or one and one half times that of iron at zero pressure.

2. An outer shell, about 1,000 miles thick, and occupying nearly six tenths of the whole volume, is essentially composed of silicate material, the substance of ordinary rocks. In the diagram

of Figure 60 the shell is left blank except for the thin circular line, which represents approximately to scale the thickness of the earth's crust, a small crystallized part of the silicate shell.

3. Between that shell and the core is an intermediate shell of mixed iron and silicate. This layer is about 800 miles thick, and represents one fourth of the whole volume. It is a layer of

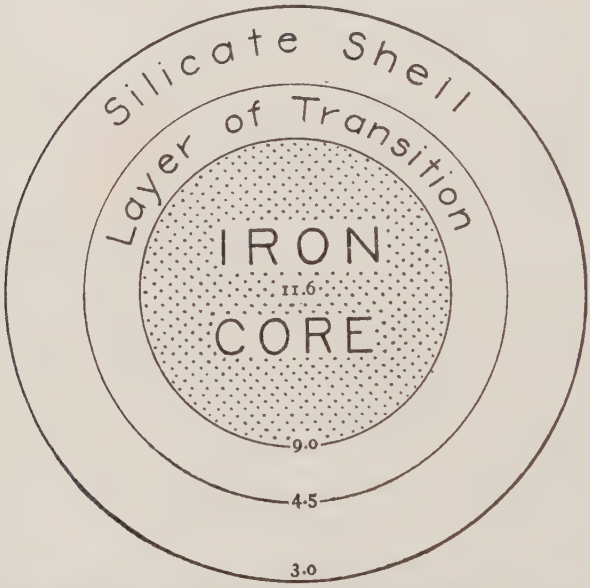


FIG. 60. SECTION THROUGH THE EARTH'S CENTER, SHOWING THE IRON CORE, THE LAYER OF TRANSITION, AND THE SILICATE SHELL, WITH DENSITIES.

transition, chemically, between the other two parts of the globe. In it the iron is more abundant below and silicate above. These mixtures are probably not crystallized, like the meteorites, but rigid non-crystalline solutions, analogous to ordinary glass at low temperature.

At zero pressure the iron would have a density of nearly 8.0, and the silicate shell a density averaging not far from 3.0. The layer of transition has an intermediate density. Allowing for compression under the earth's self-gravitation, the distribution is found to be that indicated in Table XII.

Table XII

DENSITIES AT DIFFERENT LEVELS IN THE EARTH

CONCENTRIC DIVISIONS OF THE EARTH	DEPTH IN MILES	APPROXIMATE DENSITY
Outer shell	0 (surface)	2.9 (average)
	1,000	4.5
Intermediate layer	1,000	4.5
	1,800	9.0
Core	1,800	9.0
	3,980 (center)	11.6

COMPARE DENSITIES OF:

Water	1.00
Surface granite	2.65
Surface basalt, crystalline	3.00
Wrought iron	7.85

This arrangement of the earth's material agrees satisfactorily with the changes in the velocities of earthquake waves at various depths in the earth.

Thus from seismology we get precious confirmation of the general conclusion we had reached by comparing facts from cosmogony, celestial mechanics, experimental studies on the compressibility of rocks, and the science of meteorites. All the lines of evidence converge on one solution to the problem of the nature of the earth's interior. Our globe is stratified. The layering is according to systematic change in the intrinsic or chemical differences among the successive shells. Except at the very surface, each shell is of nearly uniform composition along any level within the earth, and rests on a denser shell. At the surface we have the thin crust of crystalline rocks; this shell has been seen to have strong horizontal variation of material, as from continent to oceanic region.

In general, then, any one layer would continue to float on the one beneath, even if both were highly fluid. The layers are stratified by density.

But how is it with the relation between the two superficial shells of the earth, the crystallized crust and the glassy, basaltic

substratum? It appears that the general rule obtaining in the deeper interior of the globe is here reversed.

In Figure 56, page 100, the reader will once more note the assumed densities. The suboceanic crust is distinctly denser than the substratum material just below it. The continental part of the crust is possibly a little denser than the substratum. But if either part of the crust were submerged bodily in the substratum, the density of the submerged block would at once be increased by compression, and the block must sink some distance into the substratum. It would sink slowly, because the earth shells are all very viscous, but in the course of time the block would sink for the same reason that a stone sinks in water.

This contrast of density appears to be one of the essential conditions for volcanic action and, probably, also for the formation of mountain chains and the younger ocean basins. Practically and philosophically, the stability of the crust and substratum is a problem more significant than the problem of the deep interior of the globe. Hence time will be well spent on a study of the evidences for this cause of instability of the outermost layer of the solid earth. The study will involve a review of the facts from which arises the necessity of assuming a crust physically distinct from a glassy substratum.

Thought must be governed by the system of cosmogony we adopt. The best cosmogony seems clearly to enforce belief that the earth was at one time molten at the surface, and has since crystallized near the surface, with the formation of a strong crust. In that respect the newer view of the planet's origin agrees with the old nebular theory we learned at school. The globe was liquid at the surface because it was hot, nearly or quite white-hot. Because it was so hot, heat was radiated away very rapidly. Soon thin sheets of crust formed, as the surface began to freeze. Since the density of crystallized rock is from 5 to 15 per cent greater than the density of the corresponding liquid at the same temperature, these initial sheets of crust must have broken up and foundered in the liquid rock. The liquid rose to take the place of each flake of crust. The solid flakes

sank a few miles, or tens of miles, reaching a level where the gradually increasing density of the glassy substratum equaled theirs. At that level the flakes would stop sinking. They would melt, partially or wholly. The melting abstracted heat at this lower level. New crust-flakes joined them, with more convection of the liquid and more cooling in depth. Rapid cooling of the superficial shell of the earth was thus caused by continued overturning or convection.

As the cooling progressed, the viscosity or stickiness of the substratum kept increasing. Thicker and thicker flakes of crust were formed. Finally, these became cemented together into a continuous, relatively strong crust which, because it was continuous and not strongly disturbed by external forces, could not up-end in blocks. If it could not up-end, it could not sink; that is, it could not until some outside force broke it through, so as to cause partial submergence. See also page 309.

The thickening of the crust has been very slow, because the addition of crystalline matter to the bottom of the crust depends on the conduction of heat through the rocky crust already formed, and rock is a poor conductor of heat. The age of the earth is enormous, but there are reasons for believing the crust, even now, to be no more than 40–50 miles thick.

How are these deductions from cosmogonic theory matched by observed facts?

First, let us consider the actual temperatures in the earth's crust. At the surface the mean temperature is about 10 degrees Centigrade. At the bottom of the crust the temperature is probably not less than 1,300 degrees, the melting temperature of rock at that depth, or close to the "white-heat" of the blacksmith's forge. Hence, below the surface the temperature must systematically rise as the depth increases. This law is implicit in our cosmogonic scheme. What temperatures are actually found below the surface?

The best measurements of underground temperatures have been made at bore-holes. Table XIII gives the depths in meters (a meter is about 39 inches) of 18 well-studied bore-holes in

Europe, and also the average rate of increase of temperature with depth. We note the relative uniformity of the rates. The average rate is 1 degree Centigrade of increase for about 32 meters, or 97 feet, of descent below the surface.

TABLE XIII

THERMAL GRADIENTS IN EUROPEAN BORINGS

	TOTAL DEPTH (METERS)	GRADIENT (METERS PER 1° C.)
Kentish Town	335	28.7
Richmond	407	28.3
Searle	609	37.8
Grenelle	401	30.2
Ecole Militaire, Paris	173	29.6
Rochefort	857	27.4
Creuzot	816	28.5
Pont-à-Mousson	1,556	30.2
Martincourt	1,200	31.0
Ratum, Holland	1,309	34.0
Maris, Holland	1,300	27.7
Sperenberg	1,066	33.7
Schladebach	1,748	35.7
Sennewitz, near Halle	1,084	36.5
Lieth, near Altona	1,259	35.0
Sudenburg, near Magdeburg	508	32.3
Paruschowitz	2,003	31.8
Czuchow	2,240	3 .8
Average		31.7

Table XIV gives similar values for 23 bore-holes in the United States. That at Prickett's Creek, West Virginia, is the deepest hole yet studied and reported in print. The average rate of increase of temperature in America is 1 degree for about 42 meters, or 127 feet, of descent. It appears from the two tables that the upper part of the crust under the surface of western Europe is warmer than the upper part of the crust under eastern United States.

Many authorities regard the mean rate of increase of temperature just below the continental surfaces, the world over, to be 3 degrees Centigrade for every 100 meters of descent. This is at the rate of 1 degree Fahrenheit for about 60 feet of descent. In each of many cases the rate near the top of a bore-hole is lower than the rate measured at the bottom. The theory of a

Table XIV

THERMAL GRADIENTS IN NORTH AMERICAN BORINGS

	TOTAL DEPTH (METERS)	GRADIENT (METERS PER 1° C.)	MEANS BY STATES
Columbus, Ohio	785	40.0	40.0
Louisville, Kentucky	636	41.1	41.1
St. Louis, Missouri	923	42.9	42.9
St. John, Illinois	1,138	45.8	47.0
Chicago, Illinois	229	48.3	
Bay City, Michigan	1,053	37.5	37.5
McDonald, Pennsylvania	2,126	41.2	40.7
West Elizabeth, Pennsylvania	1,524	40.2	
Wheeling, West Virginia	1,359	45.5	
Chelyan, West Virginia	1,596	40 2	
Mannington, W. Va. (mean of 6 wells)	603 to 983	53.7	
Bridgeport, West Virginia	2,198	38.4	
Prickett's Creek, West Virginia	2,286	35.7	
Mean of 15 West Virginia wells	579 to 2,286		43.2
Average			41.8

cooling earth implies, however, that this increase of the rate of increase of temperature, that is, the acceleration of the rate, must cease at a moderate depth; at depths still greater than any reached by borings, the rate must fall off. This is one reason why the temperature gradient, actually measured in the comparatively shallow bore-holes, may not apply at depths of 20 to 50 miles. Moreover, the mean rate of 3 degrees per 100 meters represents a value chiefly derived from observations which were won at borings in sedimentary rocks, which for several reasons are likely to show specially high rates. The rate of increase of temperature in the granite gneiss, which underlies all such sediments and constitutes most of the continental crust, seems to be lower. For example, the average rate is only about 2 degrees per 100 meters at the boring recently made near Carnarvon, Cape Province, South Africa. In the great granitic terrane of the continents, this is the deepest hole yet studied with accurate results. It is safer to estimate temperatures at depths of some tens of miles by assuming a rate of increase which is no higher than 2 degrees per 100 meters.

Even with this minimum rate we get a remarkable result.

If it holds to a level 40 miles, or 64 kilometers, below the earth's surface, the temperature is there not far from 1,300 degrees Centigrade. At about that temperature and under the pressure of 40 miles of rock, basalt, the commonest of lavas, would just begin to crystallize. Still deeper the temperature is higher still and, in spite of the growing pressure, crystallization is entirely prevented. The basalt remains uncrystallized, a hot glass.

Natural glass is a hard, brittle solid which becomes molten in a furnace. The substratum is white-hot. Nevertheless, it is not highly mobile, a fluid in the ordinary sense of that word, for the great pressure makes it rigid—even more rigid than plate glass at the temperature of a room.

Borings under the deep oceans have never been made. The crust temperatures in those extensive regions are not to be directly measured. But we may reasonably hold that the rate of increase is not very different from that found under the continental surfaces. Probably the rate under the oceans is a little smaller, since basaltic rock is less radioactive than the dominant rocks of the continents. The radioactive furnace is, therefore, a little more efficient under the land than under the sea. Accordingly, in the diagrammatic section of Figure 56, the earth's crust is shown as somewhat thicker under the ocean than elsewhere.

A third suggestion of the reality of a true, comparatively thin earth's crust, overlying a thick glassy layer, is found in the rule of the condition which has already been described under the name of isostasy. During geological ages, erosion has removed from the continents masses of rocks, with aggregate thicknesses that are measurable in thousands of feet, or even thousands of meters. The corresponding solid detritus has been carried by river, wind, and marine current to great distances and there deposited as new, stratified rock. Thus there has been a tendency for the development of great negative loads on the eroded sectors of the earth, and great positive loads on the sectors covered with the new deposits. Now it is found that, under these differential stresses, the subcrustal material has flowed so

as very nearly to restore the original state of internal pressure. Below the depth of 60–100 kilometers, the pressure is almost perfectly hydrostatic. This state of balance implies great plasticity for the deeper layers in the earth. Such mobility is hard to understand at all, if the earth shells below the depth of 60–100 kilometers are crystalline. To produce flow in crystalline rock, the crystal fabric must be broken down; the tenacity due to the interatomic bonds of the crystals must be overcome. Under the small stresses, which alone could exist during the later stages in the restoration of isostatic balance, the required breakdown of the crystal fabric, even at high temperature, seems incredible.

The difficulty is greatly lessened if a non-crystalline, glassy substratum below a thin crust be assumed.

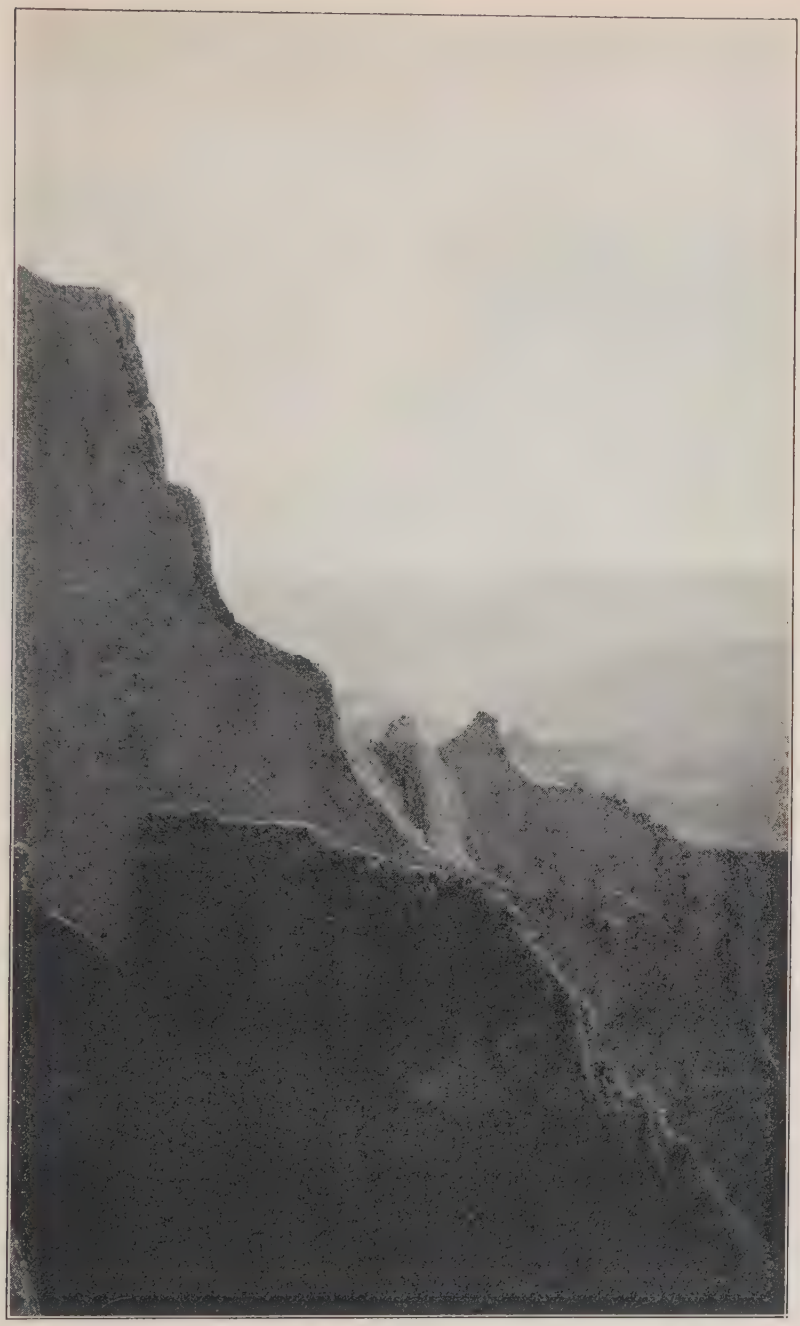
Again, the process of mountain-building seems to be dependent on the existence of the glassy substratum. When a mountain chain is formed, thick masses of sediments and other relatively light rocks are folded and rafted together. In the mountain-built belt, there is, therefore, a great thickening of such light rocks. In spite of the low density, the whole thickening body of deformed rock keeps sinking into the earth as the folding, thrusting, and rafting continue. When these horizontal displacements have come to an end, the mean surface of the new mountain-structure is below sea-level, or but little higher. Mountainous *height* is attained long afterward. This point will later be noted in more detail.

Such initial sinking of the deformed mass of rock must apparently be regarded as an isostatic adjustment. Assuming this to be true, then we are forced to conclude that the material displaced in depth has a density about equal to the mean density of the mountain structure itself. This can hardly be more than 2.8 to 2.85. The displaced material is not likely to be intrinsically less dense than basalt. Crystallized basalt at the required depth would have the density of at least 3.0. Glassy basalt at the depth of 50–100 kilometers would have the density of 2.8–2.85. This sinking of the mountain-built rocks becomes intelligible on

the assumption that the isostatic undertow is located in non-crystalline material below the crystalline crust.

Further, as will be described in Chapters VI and VII, the formation of a mountain range implies the shearing of a thick layer of rock over the rest of the earth's body through distances of scores or hundreds of kilometers. Whatever be the cause of the horizontal motion of the layer, this motion is possible only because the surface (interface) of scission or shear is located in extremely weak material. Here again we seem compelled to think of the sheared material as hot glass, for no crystalline fabric is likely to be of such low strength.

There is another relevant fact. In general, heavy earthquake shocks originate at depths less than twenty-five miles. An earthquake is due to the sudden snapping of the rocks. The rupture comes about because the earth's material has been increasingly strained through a long period of time. When the tension of the strained solid reaches a certain intensity, the solid breaks and elastic waves rush away from the fracture in all directions, and with the speed of sound in the rocky material. The slow growth of the tension is possible only when the material has true strength. The shallowness of most foci of strong earthquakes indicates that the deeper shells of the earth can not long continue to accumulate shearing tension which shall ultimately attain large amount. The implied weakness of the deeper shells is comprehensible if they are non-crystalline, but hard to understand if they are crystalline. This conclusion does not, of course, mean that no strength whatever is to be ascribed to the substratum. Its strength may be real, but it must be very small. Moreover, if the earth be rapidly strained with the rapid development of tension in the substratum, the rigidity of this glassy shell may not have time to decay sufficiently for much relief of tension by true flow. In that case the tension at great depth may become considerable; a sudden rupture at great depth may take place, with energetic shaking of the globe. On the other hand, the preparation for each of the commoner earthquakes has been leisurely, and it seems clear that the corresponding tensions were



Photograph by the Author.

FIG. 61. GREATLY ERODED 5,000-FOOT ESCARPMENT AT THE EASTERN EDGE OF THE BASALTIC PLATEAU OF BASUTOLAND, SOUTH AFRICA. THE CAMERA WAS LEVELED AT A POINT ABOUT 10,000 FEET ABOVE SEA-LEVEL.

formed in the crust, where the rocks have permanent strength and permanent rigidity of high orders. The occasional shock at depths greater than 40 miles may simply mean, therefore, that the material below that depth, while nearly devoid of true strength, shows shearing rigidity only against stresses of com-

Photograph by the Author.

FIG. 62. SUPERPOSED FLOWS OF BASALTIC LAVA, FORMING THE SOUTH-EASTERN SEA CLIFFS OF THE ISLAND OF SAINT HELENA, SOUTH ATLANTIC. THESE CLIFFS ARE 300–600 FEET IN HEIGHT.

paratively short duration. Such material would be hot glass, not crystalline rock at any temperature.

To sum up. Six different lines of evidence tend to support the hypothesis of crust and substratum—a hypothesis that appears to be decidedly preferable to the assumption of crystallinity for the whole earth.

From the temperature gradient we deduce the thickness of the overlying solid-crystalline crust to be not much more than 60 kilometers or, say, 40 miles. That the substratum is basaltic in composition is suggested by the fact that, when the crust is cracked open, hot basaltic glass gushes out. It matters not where the deep-going crack is situated, whether it crops out on land or on the sea bottom; the greater lava floods are always basalt.

One of the many places where one of these vast floods can be seen is in Basutoland, South Africa. Long ago the lavas were poured out in this region. There has been time enough for deep valleys to be cut in the hard, solidified flows. The rugged escarpment of Figure 61 is nearly a mile high, looking over the

FIG. 63. VIEW OF THE WRINKLED, GLASSY SCUM OR CRUST ON THE LIQUID LAKE OF LAVA AT HALEMAUMAU CRATER IN THE KILAUEA SINK, HAWAII.

lion-infested jungle of Portuguese Africa to the Indian Ocean. The whole cliff, rivaling in grandeur the cliffs of the Grand Canyon of the Colorado, is made of successive flows of basalt, essentially uniform from top to bottom. The stuff of our substratum here comes into actual view. So hundreds of thousands of square miles of the earth's surface have been flooded with this primitive lava emanation from a universal earth shell.

In mid-Atlantic, at the sea cliff shown in Figure 62, may be seen the outcropping edges of many flows of basalt, composing

the island of Saint Helena. The floods of lava, long since frozen solid, in which the Snake River of Idaho is busily cutting its canyon, are basaltic. In mid-Pacific the fluid lava which has been streaming about, exploding, and throwing its thundering breakers on the shores of the lava lake of Kilauea, in Hawaii, is

Photograph by Mayor, by courtesy of the Carnegie Institution of Washington.

FIG. 64. THE DEEPLY ERODED BASALTIC ISLAND OF TUTUILA, AMERICAN SAMOA; LOOKING WESTWARD FROM AUA VILLAGE OVER PAGO PAGO BAY, THE "FINEST HARBOR OF THE PACIFIC ISLANDS."

basalt (Figure 63). Still farther round the world, in Tutuila Island, of American Samoa, we have a sample of many basaltic islands of the western Pacific (Figure 64).

Such examples might be indefinitely increased in number, from every continent and from every sea basin. The universality of eruptive basalt speaks strongly for its being the stuff constituting a complete shell of the earth at moderate depth.

As yet the seismologists have not detected with certainty the physical break between the crystallized basalt of the lower part of the crust and the underlying non-crystalline or glassy

basalt of the substratum. On the other hand, they have recently suggested a means of measuring the thickness of the lighter "granitic" rock, which essentially constitutes the upstanding continents. The longitudinal or *P* waves, sent out from an earthquake center, travel through the uppermost 30 miles of the continental crust at an average rate of about 5.8 kilometers, or 3.6 miles, per second—the velocity of sound in this rocky shell. The velocity closely matches that expected if the shell is essentially granitic in composition. The geological map and structure of every continent show, in fact, that the upper part of the crust is very near granite in average composition.

At the depth of about 55 kilometers, or 34 miles, in central Europe, the velocity of the longitudinal wave suddenly jumps to about 8.0 kilometers, or 5.0 miles, per second. The speed of the longitudinal wave depends on the rigidity, compressibility, and density of the material traversed. The exact relations among these four quantities are shown by the second of the two equations on page 105.

Now it is found that, if the material below the 55-kilometer level has the properties of crystallized, basic basalt, affected by the corresponding pressure, the velocity of about 8.0 kilometers per second at that depth can be understood.

The kind of evidence for the rather sharp separation of the continental part of the earth's crust into two layers—a "granitic" layer above and a crystallized-basalt layer below—is illustrated in Figure 65. The diagram is a simplified edition of that recently published by the seismologist Gutenberg. It is a section of the 55-kilometer layer, greatly exaggerated in thickness for clearness of drawing. From the focus, or center, of an earthquake shock, waves run out in all directions. The wave-paths marked *1* to *8*, inclusive, are confined to the "granitic" part of the crust. Ray *8* is totally reflected at the bottom of this layer. On the other hand, rays *a* and *b* have plunged into the basaltic material beneath the "granitic" layer. Because of the physical differences between the two layers, all rays penetrating the lower layer, except ray *x*, are refracted or bent at the surface of con-

tact between the two layers. A wave-path like *a* or *b* traverses the basalt for some distance, impinges on the lower contact of the "granitic" layer again, is once more refracted, and emerges at the surface of the earth, not very far from the focus. Such rays as *x*, *y*, and *z* penetrate the earth to great depth and emerge at the surface far from the focus, or epicenter. For simplicity the two rock layers are supposed to be respectively homogeneous,

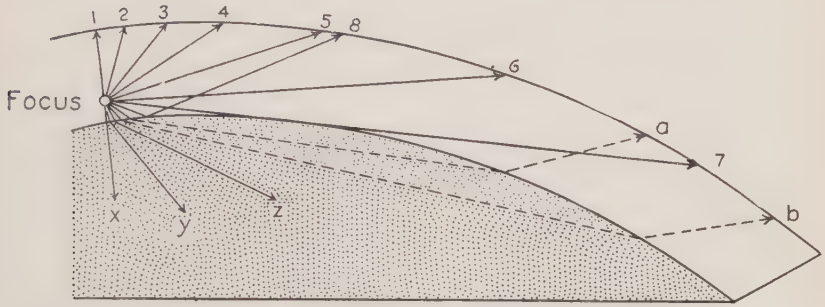


FIG. 65. SECTION ILLUSTRATING THE SUDDEN CHANGE IN THE EARTH'S MATERIAL AT THE DEPTH OF 50–60 KILOMETERS. STIPPLING REPRESENTS BOTH CRYSTALLIZED BASALT AND SUBSTRATUM GLASS.

so that the wave-paths or rays are straight. As a matter of fact they would be bent slightly in each layer because of its variation in physical properties with increase of depth. Yet the arbitrary assumption does not involve any error of principle that is important in the present connection.

All the changes of direction and speed of the waves are directly or indirectly recorded in the seismograms made at different stations on the earth's surface. From the records seismologists have been able to demonstrate this very pronounced change in the materials—technically called a "discontinuity"—in the rocks underlying central Europe. Similar studies should be undertaken in the United States and elsewhere. Meantime we seem entitled to regard the European results as very probably corroborating the other evidence for the average depth of the "granitic" material, which floats high on the earth's body and therefore forms the continents.

A final word about the nature of the substratum, the posi-

tion of which is again recalled by the diagrammatic sections of Figures 56 and 57. As already noted, it is not to be thought of as fluent, like the molten artificial glass of the glass-blower. The least pressure on the substratum glass is more than 10,000 atmospheres. That is to say, each square inch of the material is pressed as much as it would be by the weight of more than 1,000 men. Under such tremendous pressure the gas-charged glass, though white-hot, is kept stiff. Against the rapidly applied stresses set up by earthquakes, its stiffness or rigidity is twice that of good granite. The earth as a whole, in spite of its very high average temperature, is twice as rigid as steel, and half as compressible as steel, when these properties are measured by the earth's reaction to seismic stresses; the reason is the same: high compression of the material.

Where a deep-going fissure is opened clear through the crust, the all-sided pressure on the substratum material at the foot of the crack is instantly lowered. Hence the stiffness of the hot glass is suddenly lessened. The hot glass thus becomes more fluid in the ordinary sense; it rises in the crack, urged by the one-sided pressure due to the weight of the crust. Finally, the glass issues at the earth's surface, where the pressure is only that of one atmosphere. Here, then, the gas-charged glass loses nearly all of its colossal rigidity and viscosity; it races down volcanic slopes, sometimes with the speed of a race-horse. The lava cascades in Hawaii (Figure 66) illustrate the fluidity of the substratum, once it has escaped from its prison-house.

A most important point remains. Though so rigid while under the high pressure of its original subcrustal position—rigid as against earthquake waves or as against the short-period tides—the substratum will, nevertheless, yield indefinitely even under comparatively small distorting forces, if these forces be kept applied for a long time. If the substratum were crystalline, like ordinary rock, it would not so yield under such permanent small pressures; it would have notable strength. Very hot glass, even under high all-sided pressure, lacks the permanent stiffening due to a crystalline fabric. Under additional, constant, comparatively

small, one-sided pressure, it will slowly but surely flow. In effect, it acts much like pitch or tar. Practically the substratum glass has some strength, but the strength is very small.

The undisturbed substratum is, then, potentially mobile.

FIG. 66. LIQUID BASALT FLOWING OVER A SEA CLIFF IN HAWAII.

Among the consequences of this mobility are two: the possibility of volcanic action, and, secondly, the possibility of mountain chains. To these old, fascinating problems, the following chapters will be devoted.

Summary

The metaphysician has found that the real is the invisible. This is eminently true of the earth. The real earth is not its visible skin, but the visible skin plus the much bulkier hidden stuff within. This chapter has sketched the modern scientific views and suggestions concerning the true character of the planet on which we live, into which we can never look with physical eyes.

The classes of rocks making up the earth's crust have been described. The continents stand high because they are made of comparatively light rocks floating on the earth's body.

The visible rocks are only about one half as dense as the earth as a whole, which is five and one half times as dense as water. We have found two causes for this high average density: compression of the material under its own weight; and the prevalence of specially heavy material in the core, probably metallic iron. In spite of the intense compression of the internal stuff (the pressure at the center is about 22,000 tons to the square inch), it still remains capable of further condensation if new pressure be added. That is, all the earth shells are somewhat compressible, as proved from the records of earthquake waves. This means, too, that if pressure be taken off the surface, the material beneath will expand elastically. The importance of the fact will become apparent in the fifth and following chapters of this book.

We have reviewed new data showing the rate at which the temperature increases with depth below the surface. The temperatures of the deep interior are certainly to be measured in thousands of degrees Centigrade. They probably surpass the surface temperature of the sun, about 6,000 degrees, or four times the temperature of vivid white-heat.

The conclusion has been reached that the rock material below the average depth of 40–50 miles can not be a crystalline solid, like ordinary rock; it is considered to be a very hot, incandescent glass. The reality of the earth's crust is affirmed. With that conclusion the reality of a glassy substratum must be automatically assumed. Geology declares the substratum to be basaltic. Seismology as eloquently declares it to be highly rigid, when affected by distorting pressures which act for brief periods. However, geology and the principles of physics warrant belief in the great plasticity of the substratum basalt, if the pressures are long continued. The substratum is very weak, so weak that it ultimately yields to steady pressure, almost, though not quite, like a common liquid.

This mobility of the substratum is basal to nearly every important consideration to be presented in the next five chapters.

No less important is an inevitable consequence of the theory of the earth's constitution here outlined. Crystallized basalt is about six per cent denser than glassy basalt at the same temperature. Hence the suboceanic crust is in danger of foundering in the substratum, if that part of the crust be once immersed in the weak material of the substratum. Probably the same is true of the continental part of the crust, though the contrast of densities is smaller. We shall find this feature of the theory of prime significance in the problem of mountain ranges and the related problem of the ocean basins.

CHAPTER IV

VOLCANIC ACTION

We have learned that, in its reaction to seismic and other forces acting for short periods, the earth behaves like a solid, highly rigid body. The temperatures of the interior are high, far above that of white-heat or the melting-point of rock. Nevertheless, the basaltic substratum and even the deeper shells of the earth are very rigid. This rigidity is explained by the great internal pressures, due to the self-gravitation or weight of the earth's materials. The rigidity, in its turn, explains the propagation of the transverse waves sent through the body of the planet from the focus of an earthquake shock. Such waves could not be transmitted through a liquid earth. Yet the existence of lava flows shows the real liquidity or fluency of at least small fractions of the material constituting the interior of the globe. The theory of the earth which is being gradually presented must, therefore, take account of an apparent contradiction: how can the rigidity of the material inside the earth be reconciled with the liquidity of its surface manifestation?

The contradiction becomes more specific in view of the thesis offered in this chapter—that the essential element in volcanic action is the mobility of the basaltic substratum which, at the depth of about 40 miles, everywhere underlies the solid crust of the earth. The instrumental records of earthquakes show the basaltic substratum to be more rigid than good granite. Yet some of this basaltic material rises through the thickness of the crust and flows out as true liquid at the earth's surface. How can this be? How can lava be erupted from the interior of a globe, apparently so solid, so immobile? What is the mechanism of volcanic action?

Volcanic phenomena are highly varied, but there is one process common to all. That process is the rise of hot lava, or, as it

is technically called, magma, to a position at or near the surface. The temperature of the magma is far above that of incipient incandescence; that is, far above the temperature of about 600 degrees Centigrade, or 1,100 degrees Fahrenheit. The magma consists of liquid rock in which gases of various kinds are dis-

Photograph by Reid.

FIG. 67. MOUNT ARARAT, A VOLCANIC CONE, 17,000 FEET HIGH AND STANDING ABOUT 14,000 FEET ABOVE THE GENERAL LEVEL OF THE FOREGROUND.

solved. In part at least, the gases were dissolved when the earth was formed; they represent part of the original melt or solution. If the magma reaches the surface, a large fraction of the gas escapes into the air; the rest of the solution freezes in the form of a new rock, the kind of rock called igneous.

Our problems are to find the source of the magma; to explain its rise in the earth's crust; and to analyze the consequences of the displacement. First, however, let us review the kinds of volcanic eruptions at the earth's surface.

Naturally, we begin at Ararat (Figure 67). Noah seems not

to have realized that his ark grounded on the top of a 17,000-foot volcano. Ararat is an example of the familiar cone. Because the cone was gradually built up by successive explosions and lava flows, which emanated at and near a single point on the earth's surface, the whole mass may be described as the product

FIG. 68. MAYON VOLCANO OF SOUTHERN LUZON, PHILIPPINES, A REMARKABLY SYMMETRICAL CONE, NEARLY 8,000 FEET HIGH; ACTIVE IN 1901.

of a *central* eruption—eruption around a central *point*. One of the most symmetrical examples is Mayon volcano, of the Philippines (Figure 68).

A second class includes the *fissure* eruptions. In each of these instances the lava simply wells out along a crack in the crust. It emanates from a line rather than from a point, as is the case with central eruptions. Figure 61, page 117, represents the eroded edge of a 10,000-foot plateau in Basutoland, South Africa. The plateau is made up of many hundreds of lava flows, which issued quietly from hundreds of fissures. After each older flow had congealed, it was covered by younger flows. In this way a total thickness of more than a mile was accumulated.

The total area was much more than the 30,000 square miles now visible, for the old plateau has been largely destroyed by erosion.

Figure 69 is a picture of a single thin flow from a fissure in Ascension Island, midway between Africa and South America. The fissure is on the left, in the background; from it the ragged,

Photograph by the author.

FIG. 69. A YOUNG LAVA FLOW, WHICH ISSUED FROM A LONG FISSURE TRAVERSING SOUTHEAST HEAD, ASCENSION ISLAND, SOUTH ATLANTIC.

dark-colored flow of the middle ground welled out and froze on the surface of a dome of older, lighter-tinted rock. The feeding fissure is still visible as a gaping crack for a distance of more than a mile; the eruption took place not many centuries ago.

A third class is a rare type. It includes the so-called *areal* eruptions. Each of these has been characterized by the piecemeal or bodily foundering of a considerable block of the earth's crust. In this way a large body of magma has been exposed to the sky. Having reached the surface, this magma flows out on one or more sides of the area of foundering and then freezes, forming another kind of lava plateau. The lava emanates from an

area, not from a line or from a point; hence the name, areal eruption.

The 4,000 square miles of the Yellowstone Park lava, called rhyolite, appear to represent a single grand example. This extensive plateau bears the famous geysers and springs, kept hot

FIG. 70. ERUPTION OF A GEYSER IN THE NORRIS GEYSER BASIN, YELLOWSTONE NATIONAL PARK.

by the residual heat of a great mass of igneous rock, of which the rhyolite is the surface expression. Figure 70 is a view of the Norris Geyser Basin, looking beyond one of the geysers in eruption to the forested plateau of rhyolite.

Figure 71 is a section through the park showing in solid black the overflows of the rhyolite and the similarly cooled upper part of this lava, where it rose in the region of crust-foundering. The chilled rhyolite probably passes downward into a huge body of chemically similar material which, in depth, has crystallized as granite, but even now very hot granite. Such an underground mass is technically called a batholith—literally, a rock of the depths. The residual heat of this comparatively young batholith

is responsible for the periodic boiling of water and consequent steam-explosions of the geysers.

The geologist can point to not more than a half-dozen similar cases. Discussion of areal eruptions is too technical and too charged with difficulties to be here undertaken. It is better to

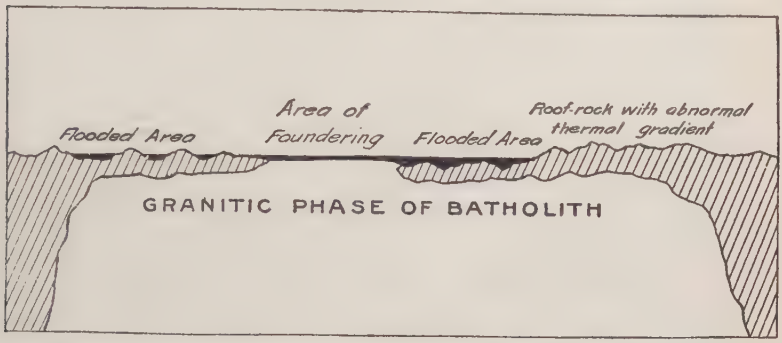


FIG. 71. DIAGRAMMATIC CROSS-SECTION OF THE YELLOWSTONE PARK PLATEAU, SHOWING THE SUPPOSED RELATION OF THE SURFACE RHYOLITE LAVA (SOLID BLACK) TO A LARGE BATHOLITH OF GRANITE, WHICH IS STILL SO HOT AS TO HEAT THE GEYSER WATERS.

concentrate attention on the genetic and physical questions connected with the first two kinds of volcanoes: central and fissure eruptions.

We start with fissure eruption, the simpler kind. Many of the fissures, through which lavas have so often welled or gushed out, are still visible as open cracks. One in Iceland is about 19 miles long, and for long distances its visible depth ranges from 400 to 650 feet. Another Icelandic fissure, 20 miles long, was opened in 1783. From it basaltic lava flowed out on both sides, one of the tongues of liquid rock reaching a length of 40 miles. One Icelandic flow covers 270 square miles.

A simple case is illustrated by Figure 72, a section across Williams Canyon, Arizona. The top of the fissure is shown at *V*, below the single, vertically lined flow *B*, which is 800 feet thick in the middle and 10 miles wide across the valley, down which the lava flowed until it solidified. This flow is exceptionally thick, because it was hemmed in by valley walls. Ordinarily

the average thickness of these plateau-making basaltic flows is about 20 feet. When one considers the fact that each flow may have run several tens of miles, rapidly radiating heat all the way, he can not doubt the initial high temperature and fluency of these outflows of primitive matter from the earth's interior.

The volumes of basalt thus extruded by successive eruptions in each plateau region are indicated by the areas involved, the

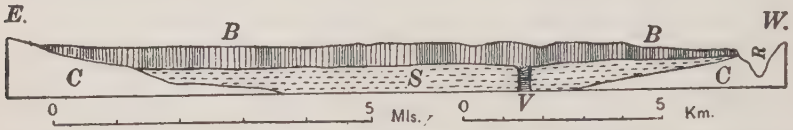


FIG. 72. CROSS-SECTION OF A THICK FISSURE ERUPTION OF BASALT AT WILLIAMS CANYON, ARIZONA. THE LAVA IS 800 FEET THICK IN THE MIDDLE; ITS VENT IS AT *V*. (AFTER LEE.)

C, crystalline rocks; *S*, sand and gravel; *B*, basalt; *R*, river.

total thickness of flows in each being several thousands of feet. The greatest basaltic plateau of North America covers parts of Oregon, Idaho, and Washington States, or about 200,000 square miles. The North Atlantic region off Scotland was flooded over an area of at least 250,000 square miles. Recent studies have shown the basaltic plateau of Argentina and Brazil to have covered originally 300,000 square miles. The map of Figure 73 shows by stippling an area of 200,000 square miles, covered by the plateau basalts of the Deccan of India. Note the scale of the map.

The simplest explanation of the major fissure-eruptions is found in the ascent of the hot, glassy substratum along fissures passing clear through the earth's crust. Since the through-going fissures go down about 40 miles, they may be appropriately called *abyssal* fissures.

The mode of formation of abyssal fissures will engage attention during following chapters, when reasons will be given for this local development of tension, breaking tension, in the earth's crust. For the present, we shall merely assume the crust to be torn open and a through-going, more or less vertical crack formed. Before the crack was opened, the pressure at the bottom of the

crust was everywhere equal to the weight of the crust. If the crust be 40 miles thick, this pressure amounts to the weight of about 18,000 atmospheres, or 270,000 pounds to the square inch. This is more than five times the pressure inside a modern cannon at the instant of discharge.

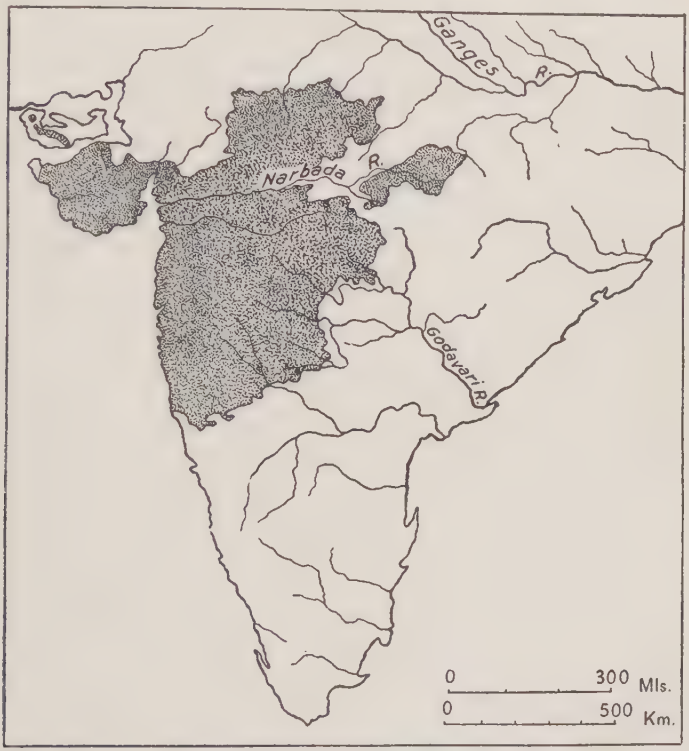


FIG. 73. LOCATION OF THE DECCAN PLATEAU OF INDIA, BUILT UP BY THOUSANDS OF FISSURE ERUPTIONS OF BASALTIC LAVA (STIPPLED).

The moment an abyssal fissure is developed, the all-sided pressure on the substratum glass at the base of the crack is greatly lowered. The rigidity and viscosity of the glass are thereby lowered at once. At the base of the crack the glass becomes mobile. Urged by the pressure of the heavy crust on each side of the fissure, the basaltic glass rises in the crack.

The density of the substratum magma is about 2.75. The average density of the crust is between 2.8 and 3.0. The heavier

crust, therefore, squeezes out the glassy lava all the way to the surface of the earth. The lava flows out on one side or both sides of the crack. Thus, following *in*trusion into the crust, we have *ex*trusion of lava on to the surface of the earth.

The rise of the basaltic lava up the fissure is further facilitated by the effervescence of the lava. Figure 74 is a photograph

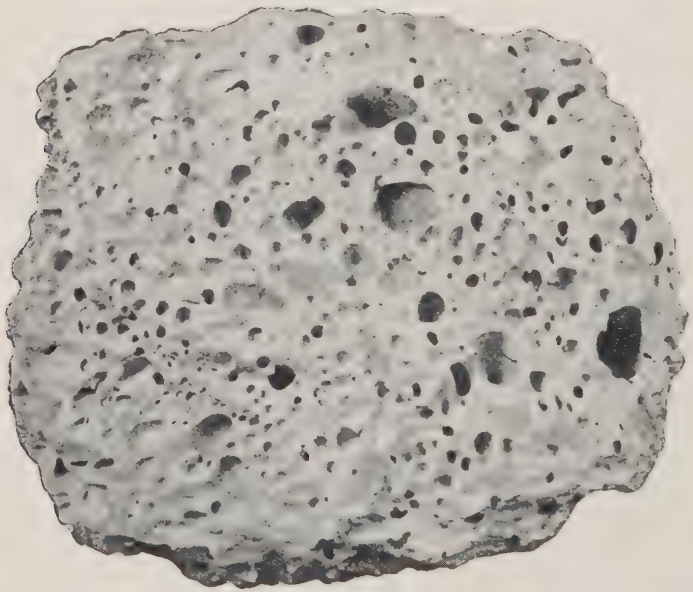


FIG. 74. A VESICULAR BASALT FROM HAWAII, ABOUT THREE-FOURTHS NATURAL SIZE.

of a piece of frozen basalt, charged with numerous pores, formerly occupied by hot magmatic gas. These cavities were caused by the expansion of bubbles of gas, which, under the great pressure of the heavy crust, had been originally dissolved completely in the substratum glass. Rising to a place where the pressure was less by about 270,000 pounds per square inch, the liquid rock could no longer hold the gas in solution. The gas came out of the solution, forming bubbles, and the whole mass was correspondingly swelled up. The density was lowered to match.

The same sort of thing goes on in a lava column as in a soda-water bottle when one removes the cork and, therewith, lowers

the pressure. Bubbles of gas instantly form in the water; the fluid mixture expands and may froth over the neck of the bottle.

Effervescence is, then, the second cause for the rise of the basaltic lava to, and above, the average surface level of the solid crust.

However, for several reasons, outflow at the surface can not be prolonged.

In the first place, as soon as the lava rises to the surface, the pressure at the base of the fissure is nearly as great as before the cracking of the crust. Hence the rigidity and viscosity of the substratum glass are restored almost to their original values, while the residual upthrusting pressure is small. The upward movement of the lava is much retarded.

Outflow at the earth's surface is retarded also in another way. The crust is strong and will not readily bend down on each side of the fissure so as to bring the full weight of the crust on the substratum material immediately adjacent to the fissure. On the principle of the shelf, cornice, or cantilever arm, the weight of the part of the crust near the fissure is supported, more or less perfectly, by the elastic strength of the crust itself. The downward pressure, due to the weight of that part of the crust, is transferred to a distance from the fissure. The upward pressure at the base of the fissure is, therefore, less than it would be if the substratum here felt the full weight of the crust.

Meantime the molten magma in the fissure tends to freeze solid, because of chilling against the cool walls of the fissure, and thus to close the passage to the surface. The new, plugging, vertical sheet of rock itself becomes part of the strong crust. Obviously, the rise of the substratum material must cease when the plugging of the fissure is complete.

Furthermore, the lava builds up its own obstruction to continued extrusion at the surface. To right and left of the fissure and just alongside it, the erupted lava is speedily chilled by radiation; it grows highly viscous and finally solidifies. Successive eruptions thus construct a dam on each side of the fissure. The height of the column of liquid lava, just ready to run over

the dam, has been increased. The total increase of its height is measured by the height of the dam. Because the liquid column is lengthened in this way, the pressure at the base of the fissure is increased. With sufficient upgrowth of the volcanic edifice at

Photograph from the Scottish Geological Survey.

FIG. 75. A VERTICAL DIKE OF BASALT, CUTTING UP THROUGH SANDSTONES; SOUTHEAST COAST OF THE ISLAND OF ARRAN. THE OCEAN WAVES HAVE ERODED AND TRUNCATED THE DIKE AND THE SANDSTONE BEDS.

the surface, the difference of pressure at the base of the fissure is annulled. The tendency for the lava to continue its ascent from the substratum is likewise annulled.

We conclude that the safety of the earth's crust, though slightly denser than the substratum, is not at all endangered by fissure eruption. The same is true for eruptions of the central

type. In neither case will the crust founder bodily, with catastrophic effect.

The many fissures which have fed the flows constituting any

Photograph from the United States Geological Survey.

FIG. 76. A NEARLY VERTICAL DIKE, LEFT STANDING WALL-LIKE, BY THE MORE RAPID EROSION OF THE WEAK STRATA ON EACH SIDE OF THE DIKE. SPANISH PEAKS DISTRICT OF COLORADO.

of the great basaltic plateaus are, of course, deeply buried by the thickened pile of individual flows. After the flat-lying beds of lava have been swept away by prolonged erosion, the rocks

filling the fissures are exposed to the light. The more or less vertical sheets of solidified lava filling the ancient fissures are called dikes. The dark-colored rock of Figure 75 is such a dike, thrust up into the sandstone of the island of Arran. Many a dike rock resists erosion better than the rocks on either side, and therefore

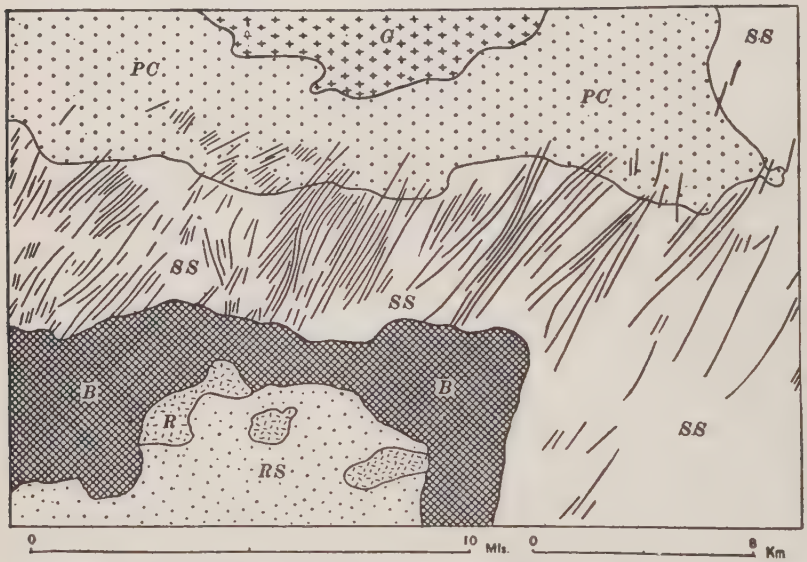


FIG. 77. MAP OF THE DIKES WHICH REPRESENT SOME OF THE FEEDERS OF THE FISSURE ERUPTIONS IN WASHINGTON STATE. (From the Author's "Igneous Rocks and Their Origin," McGraw-Hill Book Company.)

projects like a wall. Figure 76 pictures an example in the Spanish Peaks district of Colorado.

After a dike has solidified, the earth's crust may be pulled apart, cracked open again at the same place, and a second dike injected alongside the first. A third parallel dike may be formed in the same way, and so on. In Saint Helena island, I have recently studied a case where more than 200 such dikes have thus been intruded into older lava flows through successive reopenings of the same fissure. The whole group of nearly vertical sheets of rock is called a multiple dike. The Saint Helena case is the most remarkable example on record.

In each of a good many instances, renewed tension in the

crust causes a splitting along the middle plane of a vertical dike, which has already solidified, instead of along the side of the dike, as in the cases just described.

The Mount Stuart district of Washington State is a region where several thousand feet of plateau basalts have been eroded away. In Figure 77 the remnant of these basalts is indicated

FIG. 78. SMALL VOLCANIC CONES, VENTS OF THE CENTRAL TYPE, DEVELOPED ALONG A FISSURE ON THE FLANK OF MOUNT ETNA DURING THE ERUPTION OF 1865.

by heavy shading, marked with the letter *B*. North of it is a large number of parallel lines. These lines represent the dike-filled fissures, exposed to the observer because of the deep erosion. The dikes actually mapped are only a fraction of those visible in the mountains; they are really to be numbered by thousands. They are cutting up through a sandstone formation, marked with the letters *SS*, and left blank on the map. Observe the scale; the width of the area mapped is 17 miles.

We now turn to the problem of the eruption of the central type, the volcano with cone and crater. This volcanic type also originates by a preliminary fissuring of the earth's crust, followed by the ascent of the substratum basalt along through-going cracks. Such an origin is at once suggested by the common formation of typical, though small, cones along fissures from which the plateau-forming flows, just described, have emanated. The principle is illustrated in Figure 78, a map of a fissure eruption on the flank of Mount Etna. The lighter shading represents

an outflow of basalt from a somewhat curved fissure. Along the line of this crack are six little cones, each with one or two craters. Several hundreds of similar low cones were developed along the 20-mile Laki fissure of Iceland, from which in 1783 an immense eruption of the plateau type simultaneously took place.

These cones were built up by explosions of the gas-charged basaltic lava. In some cases small driblet flows of lava were

FIG. 79. THE CHAINS OF VOLCANIC CONES IN JAVA (STIPPLED). THE HEAVIER DOTS REPRESENT PRINCIPAL VENTS OF THE CENTRAL TYPE. (From the Author's "Igneous Rocks and Their Origin," McGraw-Hill Book Company.)

added to the pile of explosion débris. Small as they are, the cones are essentially like the many huge, famous volcanoes of the world. The similarity suggests a common mode of origin.

A second suggestion that eruption of the central type is due to abyssal fissuring is given by the alinement of volcanoes of the central type, so often illustrated on a map of the world. Java, over 500 miles in length, is one of the most active volcanic regions of the globe. In Figure 79 some of its many volcanic cones are indicated by stippling; the positions of their craters by heavy dots. The cones are arranged in a narrow belt, and it is observed that these volcanoes really belong to two nearly parallel systems, as shown by the nearly straight lines drawn on the map. One of the lines terminates at the island of Krakatoa, the scene of the most violent terrestrial explosion of modern times, the explosion of 1883.

The thousands of volcanoes that lift their romantic heads

out of the deep Pacific are similarly arranged along lines more or less parallel. The situation is illustrated by the diagrammatic map of Figure 80. The volcanoes of the many Pacific archipelagoes are ranged along the lines there shown. The Pacific volcanoes are almost entirely basaltic. Their alinement seems clearly to indicate repeated breaking tensions in the crust under

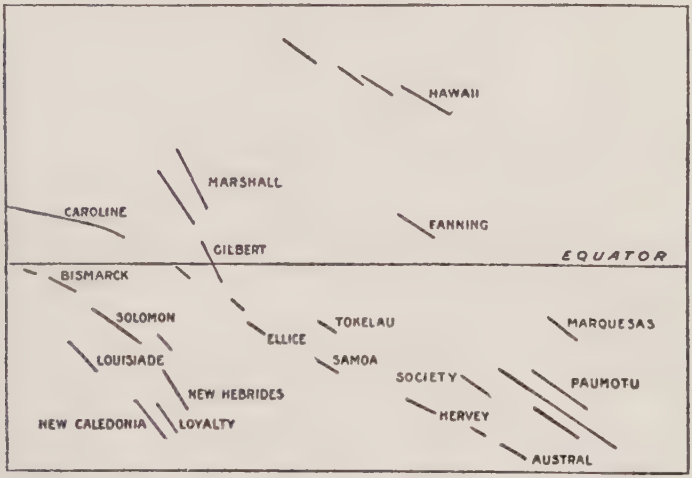


FIG. 80. TREND LINES OF THE VOLCANIC ISLANDS IN THE PACIFIC
(After Dana.)

the ocean, tensions producing abyssal fissures running nearly northwest-southeast. The process was on a planetary scale. Note the scale. The line showing the Equator is 5,000 miles long. The four offset chains of the Hawaiian volcanoes in the north have a total length of 1,200 miles.

Many other examples of alinement might be cited, but the foregoing illustrations will suffice.

Assuming the central volcano to have originated in the same general way as the fissure eruption, by the rise of substratum basalt along abyssal fissures, we still have important questions to answer:

Why is the eruption confined to points, rather than lines, along the earth's surface?

Secondly, why are volcanoes of the central type so long-

lived? Many central volcanoes have been intermittently active for tens of thousands of years. Mount Etna is much more than 100,000 years old and is still active.

Thirdly, why is their activity intermittent? Why have they alternation of active and dormant stages?

Fourthly, what determines the final extinction of every volcano?

The answers to the first two questions may be considered together. Both involve a vital principle called "gas-fluxing." This will now engage our attention.

The long life of a volcano implies large volume for the liquid lava injected into the earth's crust; the abyssal fissure must be wide. Its height is the whole thickness of the crust, about 40 miles. That many fissures have opened widely is proved by the existence of visible dikes which reach widths of thousands of feet with lengths of many miles. Lengths of 100 to 300 miles have been actually mapped. The volumes of these dike-chambers are evidently very great.

Let us, then, imagine a long, wide, vertical dike-chamber in the earth's crust—a great space filled with liquid basaltic magma. What keeps this chamber liquid for a long time?

A diagram may help to make the subject clear. In Figure 81 is shown the relation of the volcanic cone (dotted, above) to the magma chamber, shown in cross-section. The earth's crust is indicated by lining. The substratum is left blank. The lava in contact with the fissure walls solidifies by chilling against those cool walls, but long remains red-hot. That part of the magma which has thus solidified early is shown in solid black. This thin sheath of solidified basalt is an excellent non-conductor of heat, especially while still hot. Hence the much greater, middle part of the magma remains liquid, with a temperature approaching white-heat, and that for a long period of time. On the diagram the blank area inside the two wall sheaths of newly solidified rock represents this middle, still liquid, part of the magma.

Now note the small size of the mouth of the magma chamber. One might think that the lava in this narrow vent would

chill quickly, solidify, plug the vent, and so end the life of the volcano. This plugging of the vent and early extinction of the volcano are, however, prevented by the action of gas in the magma. The gas moves upward and, in so doing, transfers heat from the depths to the vent. The transfer of heat takes place by two methods.

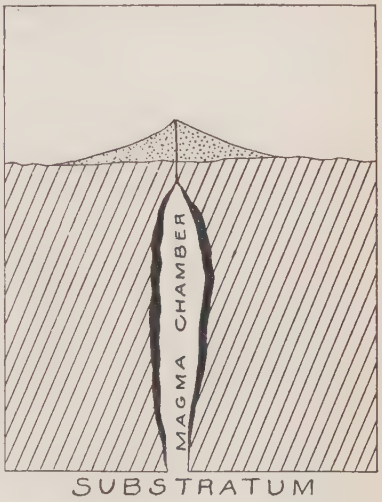


FIG. 81. CROSS-SECTION OF A MAGMA CHAMBER IN THE CRUST.

(A wide fissure filled with molten, gas-charged lava, part of which has already solidified.)

The first method: On the principle of the uncorked soda-water bottle, the magma in the chamber is effervescing. Gases, which were originally in perfect solution with the basaltic glass, are now, at the much lower pressures, no longer held in solution. They come out of the solution in the form of myriads of very minute bubbles. Moreover, as the basalt slowly freezes along the walls of the magma chamber, gas is forcibly ejected from the mass of growing crystals and forms other bubbles in the residual liquid.

Being light, these many bubbles slowly rise through the hot liquid. Figure 82 is a section of the magma chamber, not across it, but along its middle plane. This section is thus taken at right angles to the last section shown, and is longitudinal, not transverse. Volcanic cone, crust, and substratum are indicated as before; likewise the solidified and the still-liquid contents of the magma chamber. The upward streaming of gas bubbles in the liquid is indicated by arrows.

As the bubbles rise to levels of ever-decreasing pressure, they expand, becoming still more buoyant and moving, therefore, all the faster; and they bring their heat with them.

We now turn to the second method of transferring heat to the vent. Where bubbles are specially numerous, the liquid in which

they are immersed forms with them a specially light mass. This local mass of low density acts, *as a whole,* much like a stick of dry wood which is released at the bottom of a pond. The highly vesicular lava floats up rapidly, as a whole. With every foot of rise, the bubbles expand; the buoyancy increases. We shall not be surprised if the expanding composite mass of liquid and gas

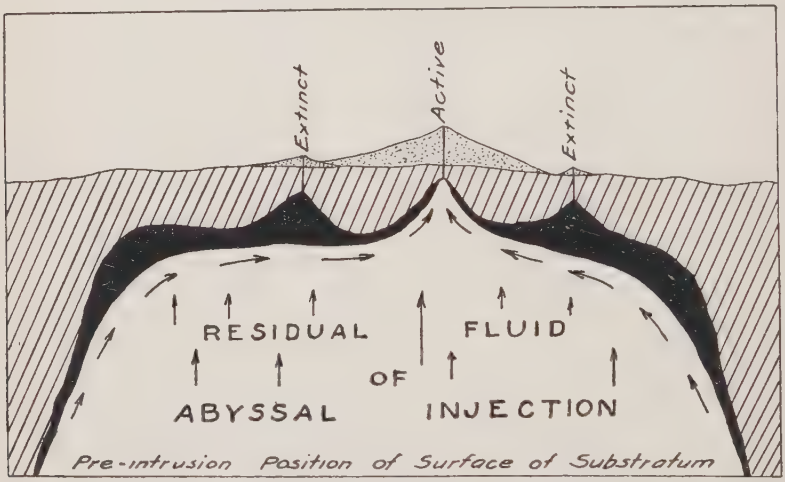


FIG. 82. LONGITUDINAL SECTION OF THE MAGMA CHAMBER ILLUSTRATED IN FIGURE 81.

jumps, fountain-like, into the air some distance. Even the non-expanding stick of wood leaps bodily out of the pond water.

The gases escape at the surface of the lava column. The density of the liquid, therefore, speedily increases, and soon becomes greater than the density of the more gas-charged liquid streaming up from below. Hence the gas-freed liquid sinks back into the depths of the magma chamber, its place being taken by a new, uprushing mass of the hotter, gas-rich melt.

Thus in two ways heat is transferred from the deep levels of the 40-mile magma chamber to the surface of the earth. In the first place, the gases are very hot, and, as bubbles rising through the liquid, they bring their temperature with them. In the second place, the heat of the deep glassy liquid is transferred upward by a kind of convection in the liquid itself.

Both processes depend upon the presence of primitive gases in the substratum magma. In Figure 82 note that, while formerly the gas streamed up to two points, one on the right, the other on the left, the final tendency has been for the gas to stream to a still higher point, shown at the middle of the upper boundary of the liquid mass. Lacking their supply of gas and therefore heat, the two lateral volcanoes became extinct. The remaining cone now receives all the advantage of the up-streaming gas and continues active; to him that hath shall be given. Meantime, the upper part of the magma in the chamber elsewhere freezes solid. A single small vent remains open at a *point* along the line of the great abyssal fissure. Eruption of the central type now rules.

This local volcanic pipe is long kept open by the rise of hot gas through the liquid, as well as by convection, in which free gas bubbles play a controlling part. The hot gas acts somewhat like a blowpipe. The tendency of the lava in the pipe within the actual cone to freeze up and stop the volcano's activity is resisted by the twofold process which, as a whole, may be conveniently called "gas-fluxing."

We now pass to the third of the principal questions: Why is the activity of a volcano *intermittent?* The vent is kept open with difficulty. Arrived at the surface, the lava is at a temperature of 1,000 degrees to 1,200 degrees Centigrade. At such temperatures, radiation of heat to the sky is extremely rapid. If the consequent cooling of the lava in a volcanic pipe, unaffected by the rise of gas, went on at its initial rate, the lava of the pipe would, during a single day, be frozen solid to a depth of several hundreds of feet. This illustrates the fact that the persistence of a volcano's activity is essentially a heat problem. Continued activity means success in a constant struggle with cold.

Because it moves under friction, the gas which is rising in the magma chamber moves rhythmically. Periods of abundant emanation of gas alternate with periods of sparse emanation. During the latter times of slow transfer of gas and heat toward the crater opening, radiation works its will, and a solid plug

forms at the crater. We have a dormant stage in the history of the volcano. In Figure 83 the older, outward-dipping beds of lava and volcanic ash, composing the cone, are shown by lines. The crater, floored with a solid plug of new rock, is shown in black.

Beneath the plug the hot gas slowly accumulates. Its pressure steadily increases. Its heat fluxes the bottom of the solid plug, as indicated by the re-entrant in the black plug of the diagram (Figure 83). When the plug is sufficiently diminished in vertical thickness, and the pressure of the gas beneath sufficiently increased, a major explosion takes place. The plug and, it may be, much of the surrounding rock are blown into the air. Dormancy is ended; a new period of activity is begun.

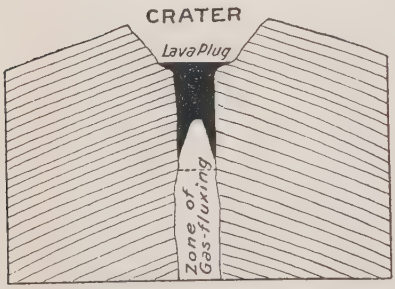


FIG. 83. CROSS-SECTION OF THE TOP OF A VOLCANIC CONE DURING ITS DORMANT STAGE, SHOWING SOME PROGRESS IN THE GAS-FLUXING OF THE SOLID PLUG. THE BROKEN LINE IN THE MIDDLE OF THE VENT SHOWS THE ORIGINAL DEPTH OF THE PLUG.

The whole process repeats itself many times, in the rhythm of the centuries. The products of explosion are deposited with greatest thickness near the vent. The effervescing lava flows are thickest near the crater. A natural result is the formation of a composite cone, one made up of beds of exploded rock fragments alternating with massive flows. In general, the cone will be symmetrical, with the quality of a Mayon or a Fuji, the celebrated sacred mountain of Japan (Figure 84).

We are now in a position to answer the fourth of our major questions: What determines the final extinction of every volcano?

The supply of gas in the great magma chamber below the cone finally gives out. Its original endowment with heat was strictly limited. So, ultimately, the intercrustal magma itself freezes solid. Meantime, the volcano at the surface has become extinct. Its life could be no longer than the time during which

the gas-feeding magma of the chamber beneath remained liquid. The volcano's life could not be lengthened by the rise of fluxing gas from the undisturbed substratum, for the gas of the undisturbed substratum, under its original high pressure, tends to re-

FIG. 84. THE CONE OF FUJIYAMA, JAPAN.

main indefinitely in solution. The region where the volcano has just become extinct will not witness more volcanic activity until a new abyssal fissure has been opened and a new body of basalt from the substratum has been injected into the fissure-chamber.

Thus the abyssal-injection theory explains the initiation, form (symmetry about a point on the earth's surface), periodic action, and final extinction of volcanoes of the central type. With the theory in mind, we shall now rapidly glance at some other actual illustrations.

For decades the most steadily active volcano has been Halemaumau, the House of Fire, in the Kilauean sink of the island of Hawaii. This most instructive volcanic area of the world has been marvelously modeled by the late George C. Curtis. The large model was presented to the Harvard University Museum by

Photograph from R. W. Sayles.

FIG. 85. PHOTOGRAPH OF A MODEL OF THE KILAUEA SINK, INCLOSING THE ACTIVE VENT, HALEMAUMAU (LEFT).

Mr. Robert W. Sayles, and is exhibited as one of the chief treasures of the museum. Figure 85 is a photograph of part of the model, showing the dark, lava-covered floor of the Kilauea sink. The sink is three miles long and two miles wide. Its highest rimming cliff stands 600 feet above the black floor of the depression. In the background is the Volcano Hotel, with a road leading from it, past the Volcano Observatory, which, under Dr. T. A. Jaggar, director, has been carefully recording the volcano's history during the last fourteen years. In front of the hotel we see large blocks of rock which have slipped down during the formation of the sink. In the middle-ground, on the left, is the dark, circular crater vent, Halemaumau, which in 1913 was 1,600 feet in diame-

ter. On the right is a conspicuous extinct crater, floored with black, frozen basaltic lava. A dozen similar craters occur in the vicinity.

We note that there is no ring of débris from explosions around the crater in the right foreground. The same is true of most

FIG. 86. KILAUEA (HALEMAUMAU) LAVA LAKE WITH A BUILT-UP RIM. PHOTOGRAPHED IN MARCH, 1894.

of the other pit craters of the region. Yet all these craters are true vents of the central type. They represent cases of pure gas-fluxing. At as many points hot gas issued from the depths and remelted the old beds of lava, like a vertically directed blow-pipe. The remelted rock sank down because some of each lava column was drained away along cracks in depth.

From Halemaumau, which has had a longer life than the other pit craters, short flows of lava have occasionally issued and now, frozen, cover the floor of the Kilauea sink. For brief periods the lava lake has risen several times to the top of the rim; at other times the lake level has sunk to a position more

than 1,000 feet below the rim. The level of the turbulent lake of molten rock has been constantly changing, up and down, but seldom during the last 18 years has the incandescent liquid sunk clear out of sight, though it is not visible at this moment of writing.

Photographs can not do justice to the ever-changing, wonderful lake itself. Figure 86 shows it at one stage, rimmed in a wall

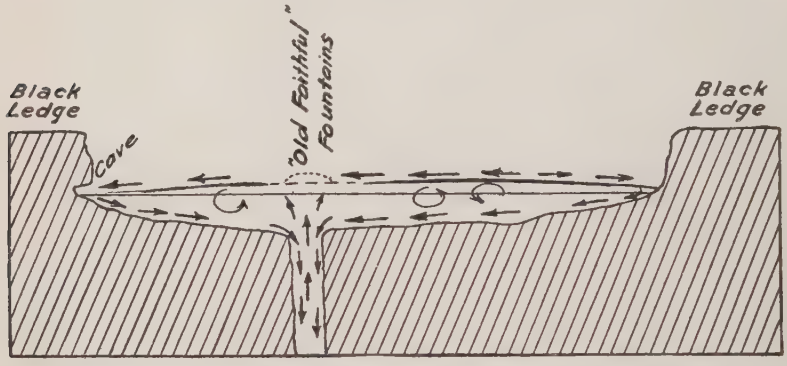


FIG. 87. DIAGRAMMATIC CROSS-SECTION OF THE LAVA LAKE AT KILAUEA IN THE YEAR 1909.

which was made of its own congealed substance. Note the little overflow tongues of liquid basalt, pouring over and solidifying, so as to increase the height of the retaining wall.

In 1909 the lava lake had a section of the kind indicated in Figure 87. The old, solid lava beds of the cliffs and floor of the lake are shaded. The liquid lake and its assumed feeding channel are left blank. By radiation of heat the liquid was chilled; hence at the surface a scum of gray, shining, more rigid glass, a few inches thick, was formed. This crust on the lake is shown by the heavier lines at the surface. The crust, while dragged by convection currents, was also constantly sliding, as suggested by the arrows drawn above the lake. While it slid, the crust was cracked by the tensions into many blocks. These blocks were tilted because the crust was being steadily domed up by the pressure of the hot gas accumulating just beneath. So thrown out of level, the crust was unstable and kept sliding in the form

of broken blocks, like cakes of ice in water, toward the open, non-crusted, brilliantly incandescent parts of the lake.

One of these constantly liquid areas of the lake surface was situated directly over the vent. There the mildly exploding lava kept in play fountains of the molten, gas-charged basalt. These

Photograph by Day & Shepherd.

FIG. 88. FOUNTAINS OF MOLTEN ROCK AT KILAUEA IN THE YEAR 1912.

explosions were so regular—once in every half-minute or so—that tourists called this small place of activity "Old Faithful."

During activity, the bases of the cliffs of the lava lake are interrupted by caves. These are due to melting of the shore rocks. The melting is facilitated by actual combustion of the magmatic gases. Study of the caves and of the general chemistry of basalt led me, in 1909, to the conclusion that chemical reactions between the gases, at and near the surface of the column of lava, were partly responsible for the heat given forth at a volcano. That conclusion has since been confirmed by actual analyses of the gases, made by the staff of the Geophysical Laboratory at Washington. It now appears clear that a volcano is a true

furnace, manufacturing some of its own heat, though most of its heat is, of course, original in the lava.

Photograph copyrighted by K. Machara, Hilo.

FIG. 89.—AN EXPLOSION AT KILAUEA IN MAY, 1924. THE CLOUD OF MIXED GASES AND ROCK DÉBRIS IS ABOUT 8,000 FEET HIGH.

Figure 88 shows a multitude of the lava fountains playing on July 8, 1912. Each is a very modest example, for fountains five times as high are often seen at Kilauea, and those with

heights of 600–800 feet have been observed on the similar lava lake of Mauna Loa, 20 miles away.

Some years before 1909 Halemaumau was dormant. Then a visitor to the pit would have looked down on a frozen lava lake,

Photograph from the Scottish Geological Survey.

FIG. 90. EJECTED BLOCKS OF ROCK FORMING PART OF AN ANCIENT VOLCANIC CONE IN HADDINGTONSHIRE, SCOTLAND. MOST OF THE CONE HAS BEEN ERODED AWAY.

a rock plug, through which, at a small opening, gas and vapor were lazily streaming.

Ordinarily, Halemaumau is able to clear away its plug by quiet gas-fluxing, without violent explosions. No heavy explosion was there registered for the 134 years previous to 1924. In May, 1924, there was a highly exceptional event at Halemaumau, a series of magnificent explosions, like that shown in Figure 89.

Imposing as such explosions are, they are merely subsidiary to the main volcanic process at all long-lived volcanoes. That

vital process is the rise of lava along abyssal fissures, followed by quiet gas-fluxing—a quiet victory in the struggle with cold.

Halemaumau and other Hawaiian craters have taught us the essence of volcanic action of the central type. Because geology arose in Europe, students of volcanoes have long been unduly

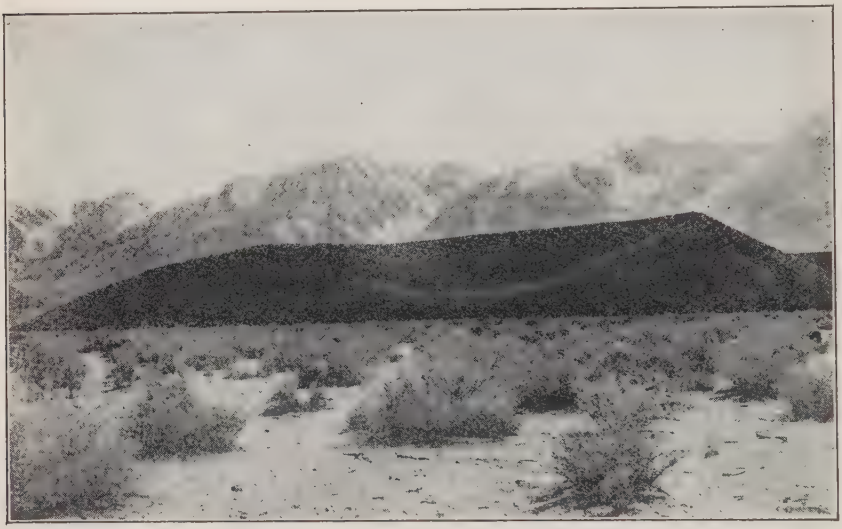


FIG. 91. A TYPICAL BASALTIC CINDER CONE, NEAR MONO LAKE, CALIFORNIA.

influenced by the noisy, dangerous Vesuvius and other classic vents of Europe. Geologists have at last come to see that explosion is merely a side show.

The high fluidity of basaltic flows is exemplified in Hawaii, with special impressiveness, at the cascades of liquid lava as they fall over the sea cliffs.

Other remarkable illustrations are found in cases where the lava has run through forests. The standing trees were covered with the liquid lava, which was so little viscous that it did not overturn the trees as it ran. Against their trunks the lava was chilled to rigid glass. As the rest of the lava flowed away, almost entirely, Liberty caps of glass were left adhering to the tree-tops.

Little wonder that basaltic flows will run 50 to 100 miles

down moderately steep slopes, in spite of the rapid radiation of heat as they lengthen! The ruling thickness of the flows is about 20 feet, here as in fissure eruptions of the basaltic plateaus.

Though explosion is an adventitious, quite subordinate ele-

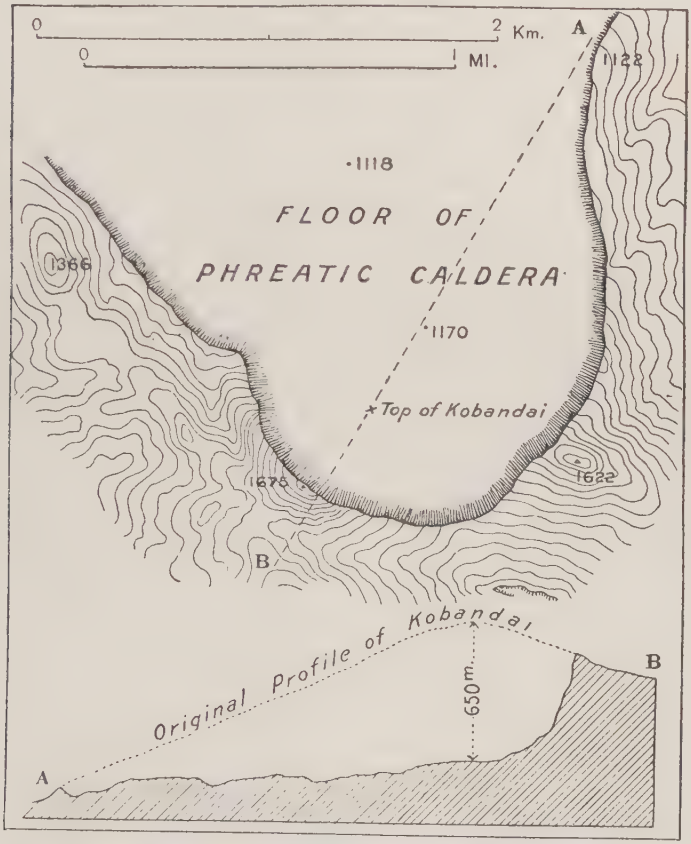


FIG. 92. MAP AND SECTION OF THE VOLCANIC CONE OF BANDAI-SAN, JAPAN, SHOWING THE EFFECT OF THE GIGANTIC EXPLOSION OF 1888. HEIGHTS IN METERS.

ment in the volcanic problem, it is important in the explanation of the cone itself. Explosions cause the accumulation of débris, such as that shown in Figure 90, a view of the ejected blocks of rock exposed by erosion on the Scottish coast near North Berwick. The form of the accumulation is typically illustrated by cinder cones. Figure 91 shows an example from eastern Cali-

fornia. In many cases, the major explosion closing the last period of dormancy eviscerates the whole cone. A deep cavity, later filled with water, results. The famous little explosion crater of Lake Nemi, of the Alban Hills, in Italy, is a case in point.

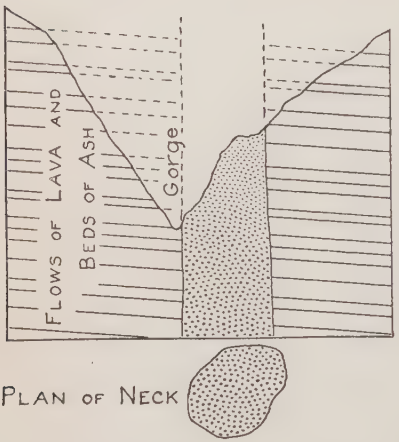


FIG. 93. CROSS-SECTION AND PLAN OF A BASALTIC NECK, FOUND IN A LATERAL GORGE OF THE IAO VALLEY, IN THE ISLAND OF MAUI, TERRITORY OF HAWAII. THE NECK IS SHOWN BY THE STIPPLING.

Not all explosions are due to the pressure of magmatic gas; that is, gas dissolved in the liquid lava. In the year 1888 the side of the Japanese cone, Bandai-San, was ripped out by an explosion of the first magnitude. The interruption of the contour lines of Figure 92 shows the part of the mountain which thus leaped into the air during a few minutes of time. The cavity, technically called a "phreatic caldera," is about two miles long and the same in width. Its maximum depth, indicated by the section below, is 650 meters, or roughly 2,000 feet.

This explosion was due to the superheating of ancient rainwater which had been trapped within the porous volcanic rocks composing the cone. The heat had been slowly conducted into these strata from the deeply buried pipe at the heart of the mountain, still hot even after a long period of dormancy. A priest who was on the summit saw a good part of Bandai-San go up in the air before his eyes. Though wounded, he lived through the catastrophe. He lived because he could breathe the air. The air was charged with steam, but not with magmatic gases, which are poisonous when concentrated as in a magmatic-gas explosion. Not a cubic inch of liquid lava was erupted during the explosion. Other cases are known (the 1924 explosion at Kilauea was of phreatic character), but most explosions are largely or wholly magmatic.

During its growth and after final extinction, a volcanic cone is subject to erosion. A water stream has cut a canyon in the lavas of the island of Maui. In the canyon is an elliptical pipe with the diameter of about 200 feet. The pipe is filled with massive basalt. In the map and section of Figure 93 the pipe is

Photograph by Grant.

FIG. 94. "LOT," A SOLID, MONOLITHIC VOLCANIC NECK (LEFT) PROJECTING ABOVE THE MUCH WEAKER BASALTIC LAVA FLOWS AND ASH BEDS OF SAINT HELENA ISLAND.

shown by stippling. The pipe was a gas-fluxed vent, melted up through the older pile of lava flows.

A somewhat similar lava-filled pipe or, as it is called, volcanic neck, is the 1,500-foot monolith in a deeply eroded part of Saint Helena Island. See the great ledge on the left side of the photograph, Figure 94. Incidentally I may note that, if Napoleon had been a geologist, he could have had a splendid time on Saint Helena.

So far we have encountered no naturalistic fact which does

not seem capable of direct explanation by the theory of abyssal injection and gas-fluxing. The theory must be supplemented, however, if we are to have a complete explanation of central volcanoes.

In the first place, some groups of volcanoes show no alignment, at once suggesting that their vents have not been fed directly from long vertical fissures passing through the crust.

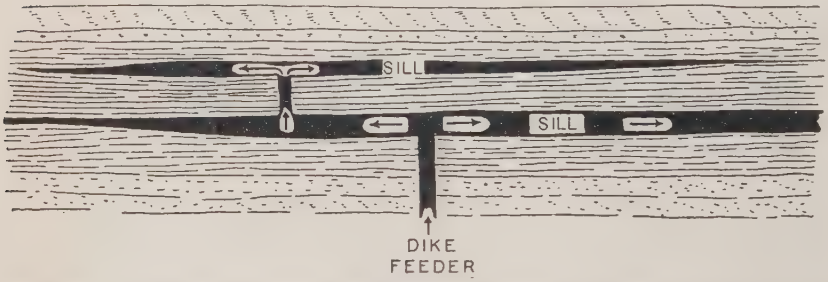


FIG. 95. DIAGRAM SHOWING INTRUSIVE SHEETS OR SILLS OF IGNEOUS ROCK IN SECTION.

Such vents are distributed much like the holes of a kitchen colander or sieve. Why this should be so is becoming clear.

Many abyssal fissures have extended from the bottom of the crust upward into bedded sedimentary rocks, but did not reach to the earth's surface. The substratum basalt has risen to the tops of the fissures and then spread out horizontally among the strata, doming up these layered rocks. When the doming is slight, the body of magma, so injected horizontally, is called a *sill*. Figure 95 is a cross-section of a series of flat-lying sedimentary rocks, which have been injected by two sills of basaltic magma (solid black). From the vertical feeding fissure, also filled with basalt, the molten rock rose and spread in the strata in the directions of the arrows. After breaking across the strata above the larger sill, the magma formed a second sill, which, again like a powerful wedge, forced apart the stratified beds of rock. An actual example, out of many thousands known, is the sill making the dark band in Figure 96.

Often the lava domes the strata more powerfully; then we

have a thick intrusive mass called a *laccolith*, or cistern-rock. A cross-section of a Montana example is given in Figure 97,

Photograph by Willis, United States Geological Survey.

FIG. 96. MOUNT GOULD, LEWIS RANGE OF THE MONTANA ROCKIES. THE DARK BAND OF ROCK NEAR THE TOP OF THE CLIFF IS A SILL THRUST INTO THE NEARLY FLAT STRATA OF LIMESTONE. THE SUMMIT IS 4,670 FEET ABOVE THE LAKE.

which represents the intrusive by solid black. A second section shows again how the surface strata of Montana were deformed by a laccolith (Figure 98), where the laccolith is indicated by a

broken-line pattern; two lenticular offshoots from the intrusive body by solid black; and the upturned sedimentary rock by conventional patterns.

Now very great laccoliths have been formed in the earth's

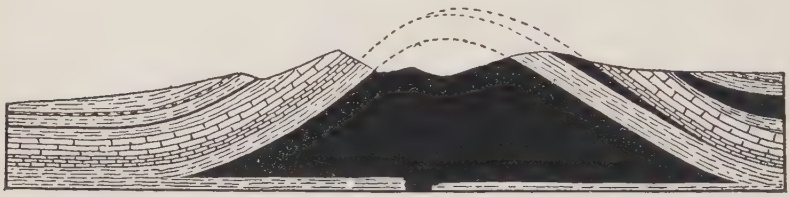


FIG. 97. CROSS-SECTION OF THE BURNETT CREEK LACCOLITH, MONTANA (SOLID BLACK). THE STRATA WHICH FORMED THE ORIGINAL THICK ROOF OF THE INTRUSIVE MASS HAVE BEEN LARGELY ERODED AWAY AND THE IGNEOUS ROCK IS EXPOSED TO THE AIR.

crust. With underground spread of hundreds of square miles, these lenses of lava lose direct liquid connection with their feeding abyssal fissures. For the connecting channel is narrow, the

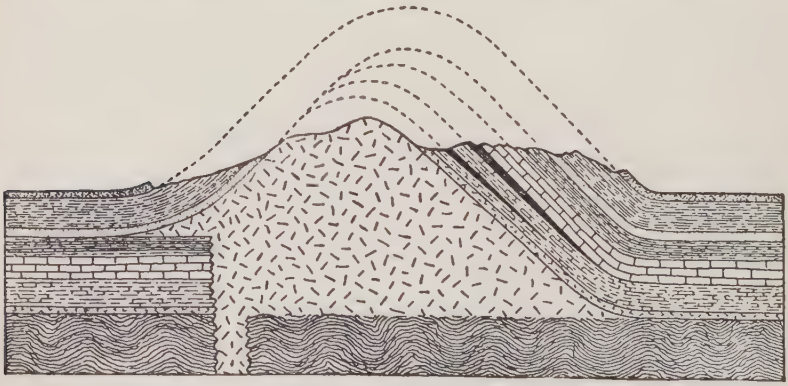


FIG. 98. AN UNSYMMETRICAL LACCOLITH AT BLACK BUTTE, MONTANA, SEEN IN CROSS-SECTION.

lava occupying the channel soon freezes solid, and the liquid laccolith becomes isolated within the crust. Fluxing gases rise from the laccolith, to collect at many points in the more or less irregular roof. At those points holes are fluxed or exploded through to the earth's surface, and as many central volcanoes are formed. These vents will not be aligned, but distributed like the holes in a sieve or colander.

An example is illustrated by a map of a part of Swabia, Germany, where there are more than 100 central vents. Figure 99 shows these in solid black.

Such vents, not fed directly from abyssal fissures, may be

FIG. 99. MAP OF PART OF SWABIA, GERMANY, SHOWING THE POSITIONS (BLACK SPOTS) OF MORE THAN ONE HUNDRED VOLCANIC VENTS WHICH APPEAR TO BE OPENINGS IN THE ROOF OF AN EXTENSIVE LACCOLITH OR SILL BENEATH THE SURFACE. (AFTER BRANCO.)

called *subordinate* volcanoes; those fed directly from abyssal fissures are *principal* volcanoes.

The marked degree of independence shown by Halemaumau and Mauna Loa, volcanoes in Hawaii, may here find its explanation. Their respective positions are indicated in Figure 100, a photograph of a model of the island, which is about 90 miles, or

145 kilometers, in maximum diameter. The place of the Mauna Loa lava lake (Mokuaweoweo) is indicated by a white dot alongside the letter M. The Kilauea lava lake (Halemaumau) is

FIG. 100. A MODEL OF THE ISLAND OF HAWAII, SHOWING THE POSITIONS OF THE TWO FAMOUS VENTS, MOKUAWEOWEO ON MAUNA LOA (LIGHT SPOT AT *M*) AND HALEMAUMAU AT KILAUEA (LIGHT SPOT AT *H*). THE TWO VENTS ARE NEARLY TWENTY MILES APART.

similarly marked near the letter H. These two vents are often simultaneously active. The one is nearly 9,000 feet higher than the other. Clearly they are not in liquid communication; else the heavy lava would all drain out at the Kilauea vent (Halemaumau). There is reason to believe that the Kilauea vent is

one of the gas-vents from a large laccolith. The hypothetical channel through which the Kilauea laccolith was injected, from the main abyssal fissure under Mauna Loa, is shown by the broken line with the arrow in Figure 101; the laccolith is shown in solid black. The scale indicates the large size of this magma

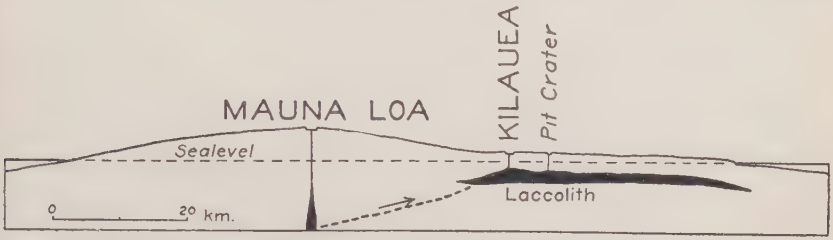


FIG. 101. DIAGRAMMATIC CROSS-SECTION THROUGH MAUNA LOA AND KILAUEA, HAWAII, ILLUSTRATING THE SUGGESTION THAT THE ACTIVE KILAUEA VENT IS A HOLE IN THE ROOF OF A CLOSED LACCOLITHIC CHAMBER OF LAVA.

chamber. Ultimately, even that big body must freeze up, and Halemaumau must become extinct.

One more leading problem remains to be noted. Many lavas are not of basaltic composition; why? This question is involved; merely the briefest statement of the answer, so far as it can yet be given, will here be made.

Under certain circumstances, later to be described, the varied solid rocks of the earth's crust locally sink into, or actually founder in, the substratum. There heated, the solid masses are melted or are dissolved by the substratum basalt, giving quite different kinds of glassy solution so far as chemical constitution is concerned. If any such solution is expelled to the surface, we shall have a lava contrasting chemically with the basalt. Solution of gases from the crust may have an analogous effect.

But again the chemical composition of either the pure liquid basalt or the contaminated liquid basalt is bound to change, as either liquid stands long in a volcanic vent. As the liquid cools, crystals begin to grow within the melt. Being heavier than the liquid surrounding them, the crystals sink, leaving a mother liquor which becomes increasingly different from the original melt, because the sinking crystals remove certain elements of that

melt and thus concentrate others in the mother liquor. This is a second reason for the origination of non-basaltic lavas.

Figure 102 is a drawing from a photograph I took in Ascension Island five years ago. The curving dark ridge of the foreground and middle ground is the lip of a basaltic crater. In the

FIG. 102. VIEW OF EXTRUDED DOMES OF HIGHLY VISCOUS, TRACHYTIC LAVA IN ASCENSION ISLAND, SOUTH ATLANTIC.
Tracing from a photograph by the author.

midst of the crater we see a rough, dome-shaped hill, and at the left background another higher dome. These domes are composed of a rock called trachyte, a pale-gray, frozen lava, strikingly different from the adjacent black basalt.

The trachytic lava was made out of the basaltic magma by one of the processes just described. Trachytic lava is much more viscous than molten basalt; as the trachyte rose in the volcanic pipe, it could not flow out horizontally far, and so solidified with the dome form.

A similar trachytic dome on the island of Tutuila, American Samoa, is a remarkable 1,700-foot hill overlooking Pago Pago Harbor.

Another example I have recently studied: a 1,600-foot dome in Saint Helena (Figure 103). Here we see the monolithic mass, allied to trachyte, resting on the bedded basalts of the cliff of the

foreground. I found the vent, up which the dome-lava rose, on the shore to the left.

So it is with hundreds of varieties of lava other than trachyte. They appear to have been derived from basalt which has been thrust up into deep-going fissures through the earth's crust, or from secondary magmas, generated by the heat of the sub-

Photograph by Grant.

FIG. 103. EXTRUDED DOME OF TRACHYTE RESTING ON OLDER BASALTIC FLOWS, ISLAND OF SAINT HELENA, SOUTH ATLANTIC. MUCH OF THE DOME HAS BEEN DESTROYED BY PROLONGED EROSION.

stratum. The chemical diversity of lavas is thus not a difficulty for the theory that substratum basalt is the heat-bringer in ordinary volcanic action. On the contrary, the chemical diversity of lavas is just what might be expected if this general theory of volcanism is true.

Finally, a few words about the occasional instability of volcanic cones. After centuries of upbuilding, a cone may be blown to pieces by a first-class explosion, or, secondly, it may disappear through bodily subsidence. The marvelous basin of

Crater Lake, Oregon, is already celebrated as the site of the bodily sinking of a cone which used to rival Mount Shasta and Mount Rainier. In place of a sharp volcanic cone, over 12,000 feet high, the tourist now sees a circular pit, six miles in diameter and 4,000 feet deep. The 2,000-foot cliffs rim the sapphire water of the lake, which is 2,000 feet deep. Heavy glaciers rested on this cone at the moment when its underpinning gave way and the central part of the cone sank vertically about two miles.

Summary

Looking back, we see that the theory of a hot, glassy, basaltic substratum, underlying the earth's crust everywhere, appears to explain volcanic action. The substratum basalt becomes highly mobile when the pressure on it is locally reduced. The reduction of pressure is expected to take place at the base of a fissure which is suddenly opened through the tensioned solid crust of the earth. The rise of the now mobile glass up the deep crack has been explained by the dead weight of the crust, aided by the effervescence of the gas-charged glass or lava. Eruptions of both the fissure type and the central type have been explained by such abyssal fissuring and abyssal injection. The prolonged activity at a central vent is attributed to gas-fluxing. We saw that the suggested theory of volcanoes also accounts for their periods of dormancy and for their final extinction. The theory explains the chemical diversity of the world's lavas, except in the case of those lavas which have been formed by the remelting of masses of the earth's crust, sunk deeply into the hot substratum. Such remelted material is also capable of eruption. The familiar granite is an example.

Under certain conditions, especially those ruling when mountains are built, granitic lavas have been formed on a colossal scale. Even in this case, however, the mobility, eruptibility, of the lavas depends on the high temperature and consequent potential mobility of the basaltic substratum.

In Chapters VII and VIII we shall see how this mobility of the substratum has been a principal condition for the develop-

ment of mountain ranges. The creation of these spectacular features has, in its turn, depended on a preliminary distortion of the globe.

The next chapter will be concerned with the distortion of the solid earth, distortion on a planetary scale—deformation of the earth's body, deformation controlled by the mobility of the material in the deep interior, far below the eruptible part of the substratum itself. That discussion will be preliminary also to an analysis of the conditions whereby the earth's crust has been so often brought under breaking tension, with abyssal fissuring, which we have found to be the first necessary process in volcanic action.

CHAPTER V

CHANGES OF LEVEL. DISTORTION OF THE EARTH

Human life, organic life in general, is absolutely dependent on a large number of delicate adjustments in the physical world. If, for example, the unique properties of water were changed even slightly, life as we know it would be impossible. If the mean annual temperature of the air or its range of temperature were only a little altered, the seats of dense population and of civilization would be transferred to great distances. Small additional changes would extinguish life entirely. That utterly delicate thing, rainfall, determines food and thus existence for mankind. Just as truly we and all other land animals exist because a very close adjustment of land and sea continues practically undisturbed.

The average height of the land is about 2,400 feet; the average depth of the ocean is about 12,000 feet, or five times as much. The volume of the ocean is 13 times the volume of the emerged parts of the continents and islands. If the solid crust of the earth were smoothed out to conform to the shape of the sea's surface, the ocean would everywhere be about two miles deep. We have already seen that the continents do persist because they are floating on the rest of the earth's body; fortunately for us, the continents are light enough to keep their tops out of water. They project, like icebergs from the sea, because made of relatively light matter. If the ocean were increased by a small fraction, or if the continental density were but slightly increased, the ocean would sweep over, and permanently cover, nearly all the lands.

Geologists know of no epoch when all land disappeared under a mantling ocean; at least, since the time when the earth was very young. Since that infant stage, hundreds of millions of

years have elapsed. This long period is what is called *geological time*. During geological time, then, each continental mass has kept at least part of its head out of water.

On the other hand, each continental surface has often been warped up and down, like the strained asphalt of city pavements, so that parts of the continents were submerged under shallow seas. Many times such vertical movements of continental regions have alternated.

These important geological facts will become clearer if we take a preliminary glance at a few examples.

In Figure 104 we recognize at once the present, familiar coast-line of North America. We also notice several shaded areas. The shading along the periphery of the Gulf of Mexico shows where the shallow sea water lay during a comparatively recent part of geological time, an Eocene epoch.

Some millions of years earlier (a Cretaceous epoch), the continental plateau of North America was cut quite in two by a shallow transgressing sea that stretched from Texas to Yukon (Figure 105). We see that the lower Mississippi Valley, Florida, a broad belt to the eastward, a long strip of the Atlantic-coast belt, and considerable areas of the Pacific slope were then also transgressed.

Much earlier still, within the limits of the Mississippian period, North America was extensively mantled by sea water in areas quite different (Figure 106). The central part of the United States and much of the Pacific Cordillera were then under water. On the other hand, Labrador was dry land, and the available geological records seem to show that most of Labrador has been dry land throughout the hundreds of millions of years since the Mississippian period.

A fourth map, Figure 107, shows the regions drowned at a Cambrian epoch, long before the Mississippian itself.

Such revolutionary changes in the physical geography of a continent were not due to enormous *vertical* displacements. Because the mean surface of the continent was only a few hundred feet above sea during the earlier geological periods, quite moderate

FIG. 104. SHALLOW SEAS TRANSGRESSING NORTH AMERICA IN THE EOCENE PERIOD.
(After Schuchert.)

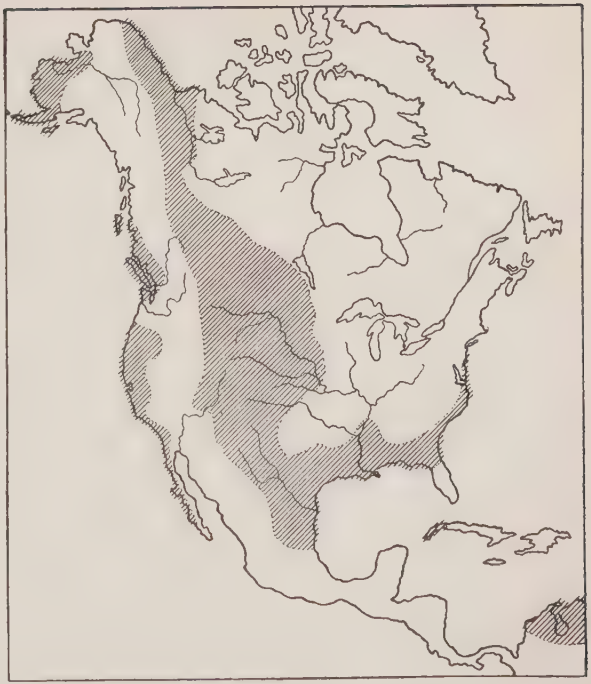


FIG. 105. SHALLOW SEAS TRANSGRESSING NORTH AMERICA IN THE CRETACEOUS PERIOD.
(After Schuchert.)

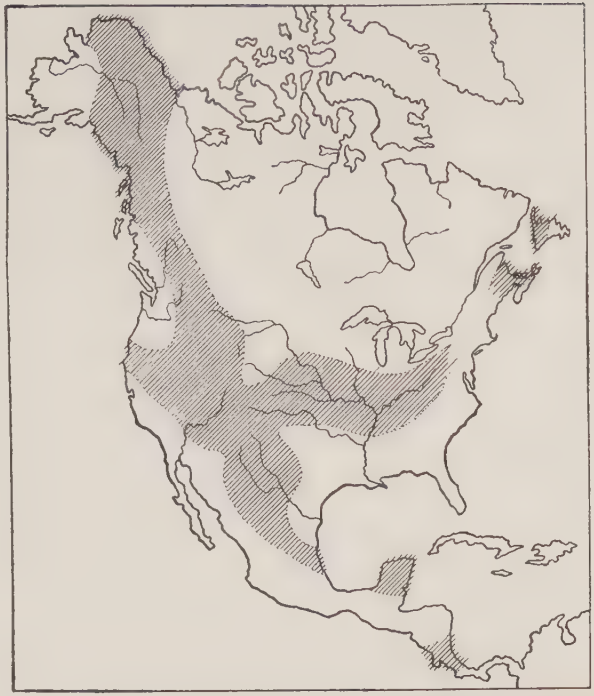


FIG. 106. SHALLOW SEAS TRANSGRESSING NORTH AMERICA IN THE MISSISSIPPIAN PERIOD.
(After Schuchert.)

FIG. 107. SHALLOW SEAS TRANSGRESSING NORTH AMERICA IN LOWER CAMBRIAN TIME.
(After Schuchert.)

warpings of the crust sufficed to cause the transgressions and regressions of the sea, which have been illustrated.

The warping of the crust was very slow, apparently in every instance. It was not accompanied by a sudden regional catastrophe. Yet the slow migration of organisms was compelled or invited with every extensive warping; the course of evolution was significantly affected. Many other effects were wrought; but we shall dwell on one particularly. A following chapter contains the suggestion that the building of mountain chains has depended on a preliminary, gentle, but very extensive warping of the earth's crust. The study of the earth's distortion is important for its own sake; it is important for its bearing on other major mysteries about the globe.

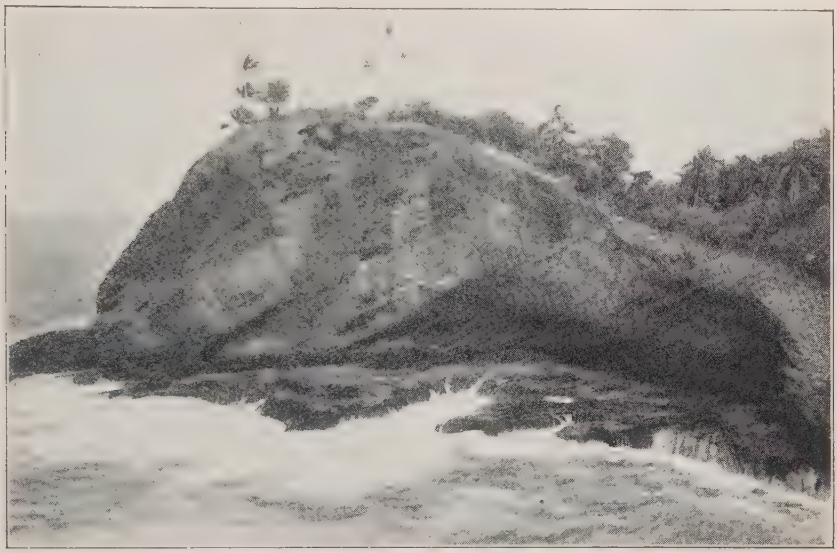
This chapter is chiefly devoted to the problem of the regional *deleveling* of the crust. By the word "deleveling" I mean "change of position with respect to levels"; the word is not in the dictionary, but it will be found useful as we go along.

The relief of the solid globe is most conveniently described by relating it to mean sea-level. To the same level, changes of the relief are referred. However, mean sea-level has not always had exactly its present average distance from the earth's center. *General* sea-level has, in fact, oscillated up and down several times in geologically recent times. Probably, too, it has oscillated much during the earlier geological periods. Before discussing the distortion of the solid globe, we shall cover some illustrations of world-wide shifts of sea-level. This second kind of deleveling has its own interest because it has caused some of the broader geographical changes of the past. However, it is here considered especially in order to emphasize the fact that not every emergence or submergence of lands along seashores means a warping of the earth's crust.

The last of the world-wide shifts of sea-level has been downward, to the extent of nearly 6 meters, or 20 feet (perhaps no more than 16 feet). The shift is small, but it is the only one for which the outdoor evidence is, as it were, immediately before our eyes. Other, greater oscillations of sea-level of this kind must

be inferred from evidence more indirect. We shall therefore dwell on the 20-foot shift, since it so clearly proves the main principle. It may be added that the discovery of the 20-foot shift is new, and not yet entered in geological text-books.

Obviously, the proof of this shift could not be assembled in



Photograph by Mayor; courtesy of the Carnegie Institution of Washington.

FIG. 108. WAVE-CUT ROCK BENCH OF AUNUU ISLAND, AMERICAN SAMOA; EMERGED BY A RECENT WORLD-WIDE SINKING OF SEA-LEVEL.

a day. The proof must be inductive and based on field work within several ocean basins—field work on all sides of the globe. We begin with the Pacific basin.

Along the shore of Tutuila Island, of the Samoan group, southwest Pacific, are many emerged rock benches and caves, which had been cut by the waves before the change of level. These features demonstrate recent emergence of this island to the extent of about 20 feet.

The neighboring island, Aunuu, has features of exactly the same kind. Figure 108 shows the benching of the volcanic rocks of Aunuu when the waves beat at a level nearly 20 feet higher than the present sea-level. The sea is now busy cutting a new

bench, which is entirely concealed beneath the frothy surface of the zone of spray.

Sixty miles to the eastward, Tau and Ofu, islands of the same group, bear rock benches of the same height. Figure 109 is a view of the emerged bench on Tau. It shows how the ruthless waves had cut into the dipping beds of volcanic material. Simi-

Photograph by Mayor; courtesy of the Carnegie Institution of Washington.

FIG. 109. WAVE-CUT ROCK BENCH OF TAU ISLAND, AMERICAN SAMOA; EMERGED BY A RECENT WORLD-WIDE SINKING OF SEA-LEVEL.

lar evidences of emergence to an equal amount are found along many miles of the shore lines on the main islands of American Samoa.

About 140 miles east of Tau, Rose atoll, the last of the Samoan chain on this end, shows recent emergence to an amount which appears to be exactly equal to that determined at the three other islands.

If four islands, thus strung along a chain 200 miles long, exhibit evidence of having emerged equally and at the same time, then we at once suspect the emergence to be due to something else than crustal warping; it would seem almost impossible for

independent upheaval of the crust to be so uniform throughout a stretch 200 miles long.

Nearly half-way round the world, at Saint Helena in the South Atlantic, is a low rock bench, cut into the lavas of this volcano (Figure 110). The cliffs above the bench are punctuated with dry sea-caves. From opening to rear, one of these caves is

Photograph by the Author.

FIG. 110. WAVE-CUT ROCK BENCH AT JAMESTOWN, ISLAND OF SAINT HELENA, SOUTH ATLANTIC; EMERGED BY A RECENT WORLD-WIDE SINKING OF SEA-LEVEL. THE VERTICAL SEA-CLIFFS WERE CUT IN THE GREAT PILE OF BASALTIC LAVA FLOWS WHEN THE MEAN SEA-LEVEL WAS WELL ABOVE THE VISIBLE ROCK BENCH.

about 120 feet long. Its floor is covered with thousands of water-worn pebbles, now dusty because untouched by the surf. Careful study of many similar benches and caves along the Saint Helena shore showed that here also the emergence was recent, uniform, and about 20 feet in amount.

Two thousand miles to the southeast is the Cape of Good Hope, where the Atlantic waves have cut caverns in old granite underlying a cover of Table Mountain sandstone. One of these caves, shown in Figure 111, is floored with large water-worn boulders, now thickly coated with dust. Near by is an emerged rock bench, cut in the sandstone. In the photograph (Figure

112), the man is standing on the bench. The white patches are those of salt, evaporated from the spray which is sent flying over the bench when the South Atlantic rages. On the right is the end of the Cape itself. Caves and benches here also prove recent and sensibly uniform emergence to the extent of about 20 feet.

Marine terraces, indicating similar emergence, are found

Photograph by the Author.

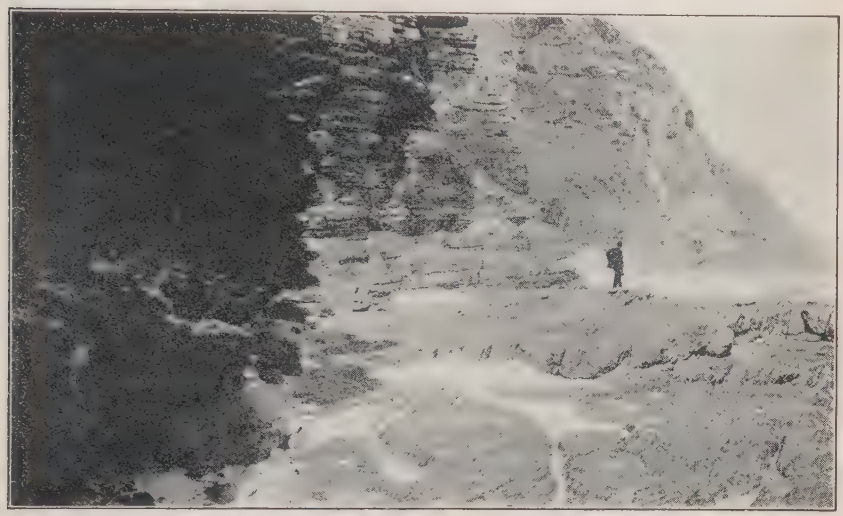
FIG. 111. CAVE CUT BY THE OCEAN WAVES IN GRANITE AT THE CAPE OF GOOD HOPE, JUST BEFORE A RECENT WORLD-WIDE SINKING OF SEA-LEVEL; THE GRANITE IS CAPPED BY SANDSTONE.

along the Atlantic coast from near New York to the Gulf of Mexico; for at least 1,000 miles along the coast of eastern Australia; along hundreds of miles of the southern and western shores of Australia; along the coasts of Brazil, southwest Africa, west Africa, and many islands of the Pacific, Atlantic, and Indian Oceans. In all these and many other published cases, the emergence is recent as well as of the same order of magnitude. Judging from the condition of benches, terraces, and caves, the emergence seems to have been simultaneous on every shore.

We do not find similar accordance of shore features within regions now undergoing independent uplift or subsidence; examples are Scandinavia, Japan, and Alaska. These local exceptions

prove the rule. Field studies in *all* the ocean basins, Atlantic, Pacific, and Indian, show that there has been a world-wide sinking of sea-level, the land at most places remaining quiet.

One naturally inquires for the cause of the lowering of sea-level. The best explanation seems to be an increase of the existing glaciers, particularly the ice-cap of Antarctica. For ice-caps,



Photograph by the Author.

FIG. 112. BENCH CUT BY THE ATLANTIC WAVES IN HARD SANDSTONE AT THE CAPE OF GOOD HOPE AND EMERGED BECAUSE OF A RECENT WORLD-WIDE SINKING OF SEA-LEVEL.

like all other glaciers, are formed by evaporation of sea water and its subsequent precipitation, as snow, on the lands. The withdrawal of enough water from the ocean to supply only a fraction of the Antarctic ice-cap would lower general sea-level 20 feet.

This increase of the ice-cap or caps has been tentatively referred to late-Neolithic time, about 3,500 years ago. At that approximate date there was some chilling of the northern hemisphere at least, following a prolonged period when the world climate was distinctly warmer than now. Late-Neolithic man lived in Europe 3,500 years back.

Much greater sinking of sea-level must have taken place dur-

ing each of the several stages of the Glacial period, when ice-caps comparable to the whole of the existing glacier of Antarctica were formed.

The shaded areas of Figure 113 represent the sites of the larger ice-caps; smaller masses of ice are indicated in solid black. By arrows the eye is drawn to glaciated tracts, which, though small, are significant because of their low latitudes. The sinusoidal projection chosen for this map is an equivalent or equal-area projection. Since areas are not distorted, Figure 113 gives a direct idea of the extension of ice within the limits of the Glacial period.

In North America the three main ice-caps, called the Labrador, Keewatin, and Cordilleran glaciers, coalesced to form at maximum 4,000,000 square miles of ice (Figure 114).

The maximum thicknesses of the ice-caps have been estimated by glacial geologists as at least 6,000 feet, or 2,000 meters. Some authorities prefer a maximum of 10,000 feet, or more than 3,000 meters, for the North American ice-cap. The uncertainty as to the exact figure is due to the absence of mountainous relief around Hudson Bay and other central gathering grounds for the ice. Where the relief is strong enough, it is easy to locate rather closely the upper limit of an ice-sheet. Thus, at the Columbia River valley, on the boundary between British Columbia and Washington State, and therefore near the southern limit of the Cordilleran ice, that glacial mass attained a thickness of more than 6,000 feet.

It is becoming increasingly probable that most, if not all, the ice-caps shown in Figure 113 were essentially contemporaneous. When at maximum, their total volume was great. It appears to have been so great that sea-level was everywhere lowered about 150 feet at least; so vast was the volume of water which was evaporated from the ocean to form the ice-caps.

Imagine what the shores of the world were like in those days. The lands had been somewhat enlarged at the expense of the sea areas. The waves then beat, not on rocky shores as now, but almost universally on banks of mud and sand, which before the

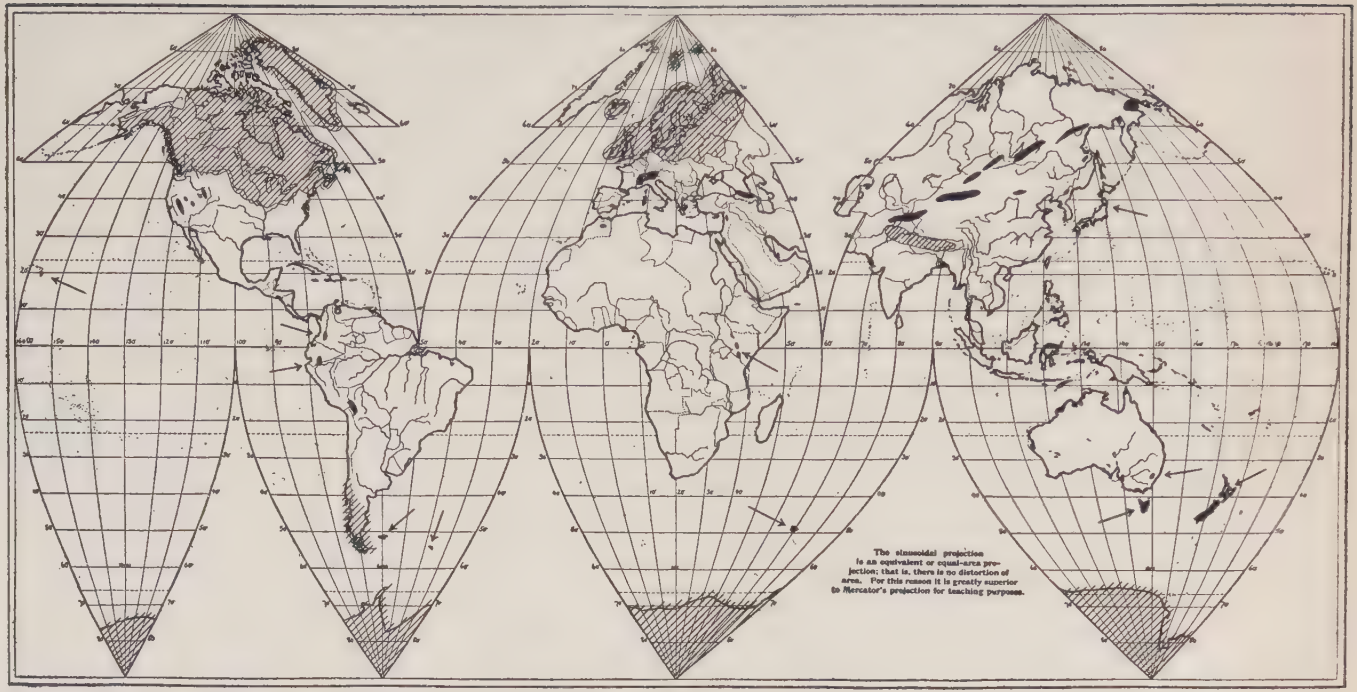

The sinusoidal projection
is an equivalent or equal-area pro-
jection; that is, there is no distortion of
area. For this reason it is greatly superior
to Mercator's projection for teaching purposes.

FIG. 113. MAP OF THE WORLD, SHOWING THE DISTRIBUTION AND AREAS OF THE PRINCIPAL ICE-CAPS OF THE GLACIAL PERIOD. (GOODE'S BASE MAP USED, UNIVERSITY OF CHICAGO PRESS.)

FIG. 114. THE COMPOSITE ICE-CAP OF NORTH AMERICA AT THE MAXIMUM OF GLACIATION. (After Chamberlin and Salisbury in their "Geology," Henry Holt and Company, New York.)

change of level had been built by waves and currents. Marine organisms were long affected by the masses of mud kept suspended in the water by the surf. Many species, sensitive to mud-baths, were handicapped in the struggle for life. For example,

corals, which were adversely affected also by the low temperature of the time, were unable to build strong reefs. Hence the waves could attack shelves and offshore banks, cut them down a little, and widely smooth them. On the platforms thus finally prepared, the existing marvelous atolls and barrier reefs in the tropical ocean began to grow. In Figure 115 the surface of one

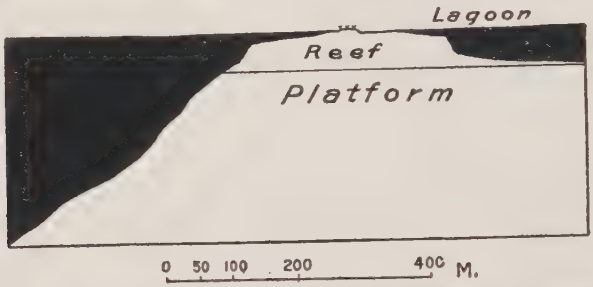


FIG. 115. CROSS-SECTION OF A TYPICAL LIVING CORAL REEF AND THE PLATFORM ON WHICH IT RESTS. SEA WATER IS SHOWN IN BLACK; THE OPEN OCEAN ON THE LEFT, THE REEF LAGOON ON THE RIGHT.
Scale in meters.

such platform is shown at the depth of about 200 feet below present sea-level. When the continental glaciers were full-bodied, the surface of the sea was not far above that lower level. Afterward, when the world climate warmed up and ice-water was returned to the ocean, the level rose the 150 feet or so. The corals took root as the slow rise started, and built up the reef at equal pace. The present relation of reef and platform is shown in the section. The warm and specially clean water of post-Glacial time has given reef corals specially favorable conditions for growth. The map (Figure 116) of the famous Funafuti atoll, reproduced in the model at the Harvard Museum, shows depth of water in the lagoon and outside the outcrop of the reef, which in nature is covered with its millions of animals. The flatness of the lagoon floor is evidently the work of cutting and filling by waves. The reef itself is narrow because so young, not very many thousands of years old.

Another example is the Suva Diva atoll, in the Indian Ocean. It is 40 miles in diameter, or over twice as wide as Funafuti atoll.

Its form and cross-section also bear out the theory of origins so briefly sketched, a theory which contrasts with Charles Darwin's

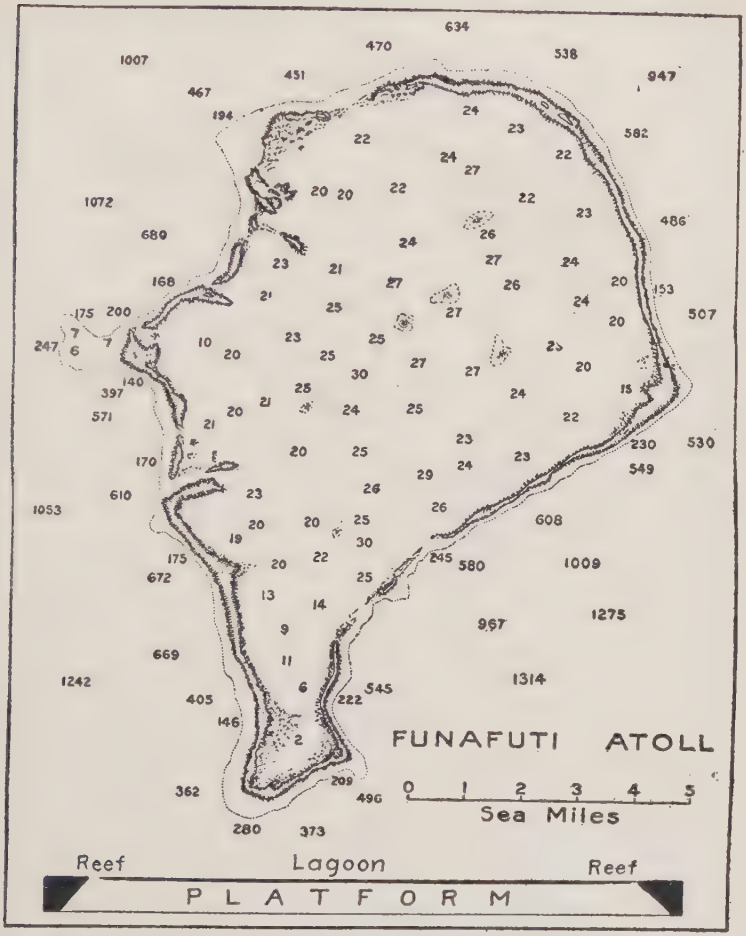


FIG. 116. MAP AND CROSS-SECTION OF THE FUNAFUTI ATOLL, SOUTH PACIFIC.

Depths in fathoms (six feet to one fathom). In the section water is shown in solid black.

well-known explanation of atolls and barrier reefs. Darwin suggested that these reefs owe their forms to actual sinking of the earth's crust over very great areas within the tropical belt. Such distortion of the solid earth need no longer be assumed, inasmuch

as the late-Glacial rise of sea-level accounts more adequately for the many facts known about the coral reefs.

Paleolithic man witnessed these notable oscillations of the ocean's surface. When the sea-level was low, he doubtless set-

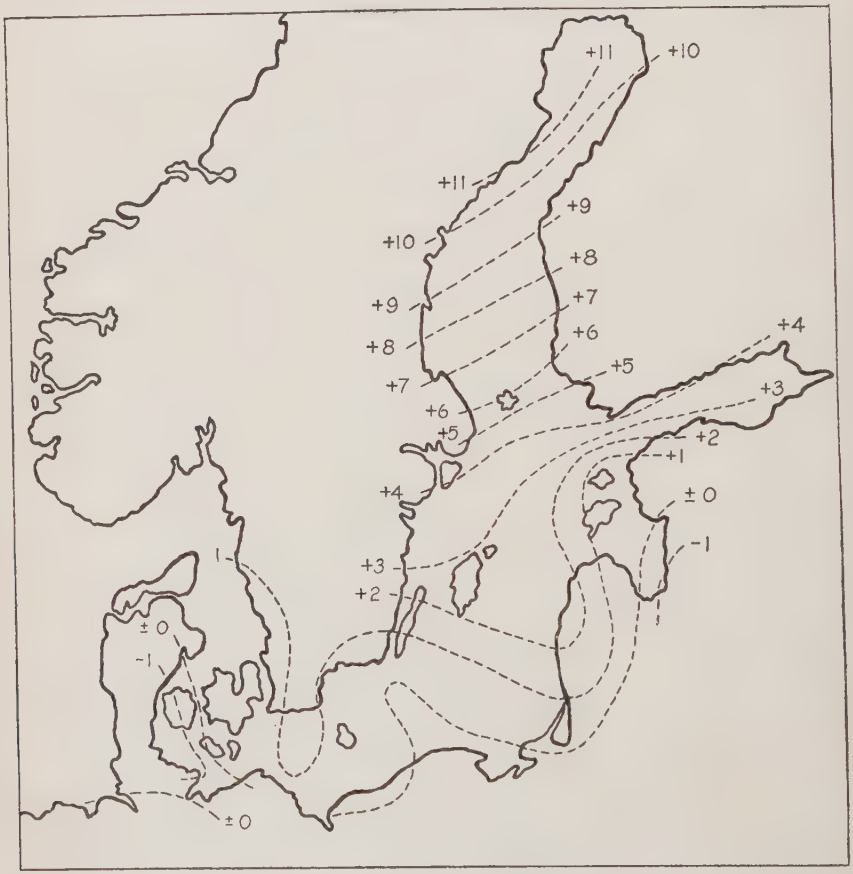


FIG. 117. CONTEMPORARY WARPING OF SCANDINAVIA. (After Witting in Salomon's "Grundzüge der Geologie," E. Schweizerbart, Stuttgart.)

tled on the shore and along the fringes of river deltas. All such sites are now deeply submerged. One cannot but speculate as to the handicap for the archæologist who wants to know all about ancient man.

We shall now consider our main subject, the *regional warping of the earth's crust.*

The form of the solid earth is being suddenly changed in those regions that are subject to violent earthquakes. In a few seconds, minutes, hours, or days extensive areas are there lowered or raised. Other regional distortions are going on more slowly, but at measurable rates. The rapid and slow movements may be detected in the same district.

For instance, Japan, which so often has had sudden vertical displacement of the land surface and sea floor, is noted also for the more leisurely warping of the ground. Through slow movements of the crust, some of the Japanese harbors are said to have become shallowed by one foot in ten years; other harbors, even one foot in three years. Vessels of deep draft can no longer enter. Mooring posts are now nearly 200 feet inland. Fishermen have to go farther out from shore to find the proper depth for casting their nets.

But other parts of Japan have slowly sunk at rates of from one foot in 16 years to one foot in five years. Accordingly, great rocks, formerly visible, are now submerged at low tide. Old settlements have been drowned. River valleys have been submerged and, in spite of some inwash of bottom mud and sand, are still to be mapped with the sounding lead.

A second example of slow contemporary warping is even more celebrated. Tide-gauges show the northern end of the Baltic Sea area to be rising now at the rate of about ten millimeters a year, or one inch in two and a half years. In Figure 117 the broken lines join points of equal change of level; the amounts of annual deleveling are shown in millimeters. Opposite the Gulf of Finland, the rise of the ground is half as rapid as in the north. Along the Baltic coast of Germany, the crust is stationary. Southern Denmark is sinking at the average rate of nearly one millimeter, or 1/25 of an inch, per year.

Similarly, as shown by gauge records, the region including Lake Superior and the northern parts of Lakes Michigan and Huron is being slowly tilted toward the south-southwest.

The cause of the tiltings in the Baltic and Great Lakes districts has been discovered, and its study throws light on the con-

ditions leading to slow but drastic changes of the relief of whole continents. We shall do well to review some results of this study.

FIG. 118. EXTENT OF THE LAST ICE-CAP IN NORTHWESTERN EUROPE, AND THE DIRECTIONS OF THE FLOW OF ITS ICE (ARROWS).
(Adapted from W. B. Wright in "The Quaternary Ice Age," Macmillan and Company.)

The last European ice-cap of the Glacial period was thickest over the northern part of the Baltic area. Thence, as shown by arrows in Figure 118, the ice flowed westward and northwestward over the high mountains of Scandinavia to the Atlantic floor; northward into the Arctic basin; eastward over Finland into

Russia; and southward into Germany. For a time this main ice-cap was confluent with the independent ice-cap of Great Britain.

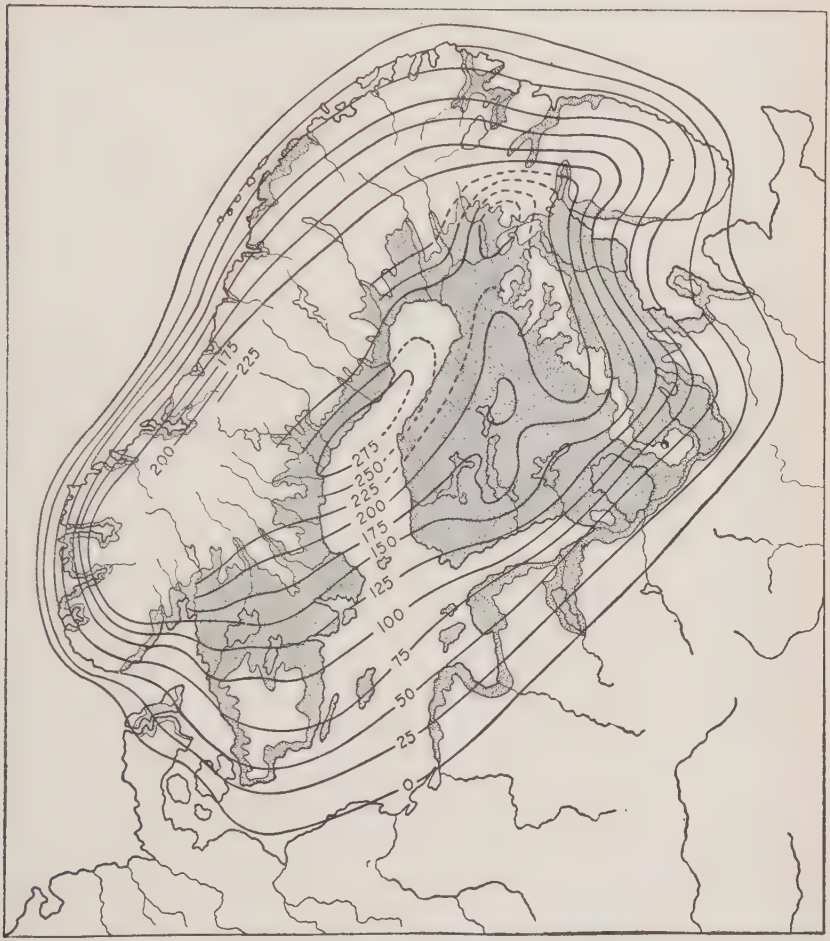


FIG. 119. EXTENT OF THE "YOLDIA" SEA WHICH TRANSGRESSED SCANDINAVIAN AND FINNISH TERRITORY JUST AFTER THE LAST SCANDINAVIAN ICE-CAP MELTED AWAY. THE AMOUNT OF THE SUBSEQUENT RISE OF THE GROUND BECAUSE OF THE RELIEF FROM THE LOAD OF ICE IS INDICATED BY THE LINES, MARKED IN METERS OF UPLIFT. (After W. B. Wright in "The Quaternary Ice Age," Macmillan and Company.)

About 40,000 years ago the Scandinavian sheet of ice began to melt away; slowly at first. Fourteen thousand years ago its edge lay at the southern border of Sweden. Five thousand years

later the ice was reduced to separate and relatively small patches on the uplands northwest of the Baltic. The succeeding 9,000 years constitute post-Glacial time.

At maximum the Scandinavian ice covered about 1,500,000 square miles. Its maximum thickness was at least 6,000 feet; its average thickness, probably more than 3,000 feet. The weight of the ice gave an average pressure of 80 tons or more on every square foot so covered. When the size of the weighted area is considered, one is not surprised to learn that the earth's body yielded under the gigantic load. Under the load the earth's crust was basined. The basin finally became nearly as extensive as the ice-cap, and at its center reached a depth somewhat greater than 900 feet, or 275 meters. Owing to the stiffness of the earth's materials and the sluggishness of their response to deforming forces, the basin *persisted long after* the ice melted away. The lower parts of Scandinavia and Finland were kept submerged under the sea (Figure 119). For some thousands of years the Baltic Sea, including the Gulf of Finland, was larger than at present; the Norwegian coast belt was lower than now, and considerable strips of country were there submerged.

During the submergence the waves of sea and ocean built beaches, and also cut rock benches and sea cliffs. The land ultimately began to rise. Those stable records of the old strand-lines were preserved. The actual amount of uprise was somewhat greater than that shown by the highest beach or bench, because uplift had begun already before much of the ice was melted away. Wherever ice lay, of course, permanent strand-marks could not be made.

Figure 119 illustrates the distortion of the country so far as actually registered by the highest strand-marks. The stippled areas show where the sea transgressed Scandinavia just after the ice melted away. The heavy concentric lines are respectively drawn through points of equal uplift of the old shore margin of that temporary sea. The lines are drawn with an interval of 25 meters, or 82 feet, between the successive pairs. Note that the maximum uplift was inside the innermost of these lines. For

lack of information, all of the lines are not complete. It is clear, however, from a comparison with Figure 118, that the greatest uplift was close to the point where the ice was thickest; that is, near the northern end of the Baltic.

In principle, quite the same kind of warping took place on our side of the ocean, after the Labrador ice-cap melted away.

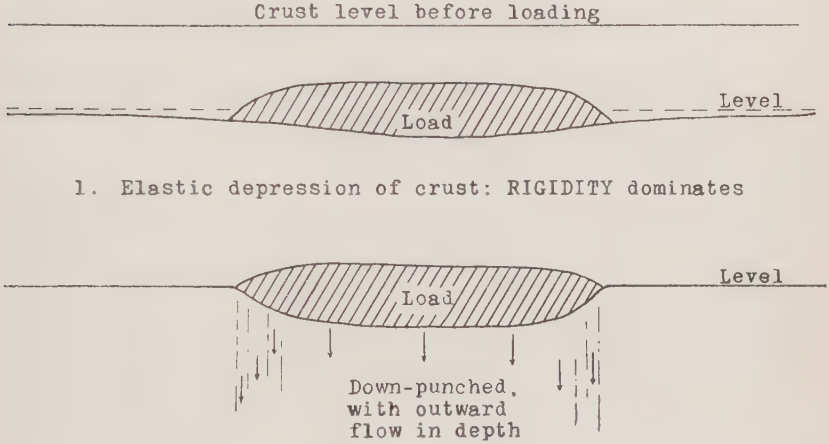


FIG. 120. DIAGRAMMATIC CROSS-SECTIONS ILLUSTRATING HOW THE EARTH'S CRUST HAS BEEN BASINED BY A GLACIAL LOAD. THE BROKEN LINES OF THE LOWER SECTION REPRESENT DISTRIBUTED FAULTS EACH OF SMALL DISPLACEMENT.

A suggestion as to the mechanism of the basining may be offered. The earth is an elastic body. It has rigidity, or resistance to distorting force, and it is slightly compressible. When a load of ice was formed on the land, the first effect was an elastic depression of the rock surface under the ice, and also of a broad belt of the rock surface all around the ice. See the middle section (*1*) of Figure 120. In this initial elastic effect, rigidity dominated the deformation of the globe. After a certain time, however, the rigidity decayed, and the earth's crust, breaking as it sank under the ice, was sheared down vertically, while in the broad peripheral belt the crust was released from its elastic

bond and was sheared upward so as there to attain its original level. The sector of the earth beneath the ice-cap thus came to feel the full weight of the load of ice and was thereby compressed. The crust was correspondingly basined. The basin seems to have been formed by down-punching along many widely distributed faults, each of very small displacement. The effect was analogous

Photograph by Grenfell.

FIG. 121. BOULDERS DROPPED ON THE ROCK LEDGES OF LABRADOR (SAEGLEK BAY) AS THE LABRADOR ICE-CAP MELTED.

to that produced when metal is punched with a die. Moreover, and still more important, since the material of the earth's interior is weak, it flowed outward from the glaciated sector on all sides. There is reason to believe that this flow chiefly occurred at great depth in the earth. The deep flow of material further depressed the crust under the ice-cap and accentuated the basin.

It may interest the reader to see how such crustal warping has been proved. The Labrador ice-cap left multitudes of boulders peppered over the ledges of solid rock (Figure 121). Initially the shore belt, which had here been depressed from 250 feet to 500 feet by the weight of the ice, was also covered with similar boulders; for the thick ice had displaced the sea water for a long

distance into the Atlantic. As Labrador slowly rose because of the removal of the ice-load, the waves rapidly washed the boulders down and built them into coarse beaches. The wave-washed rock surface is represented in the accompanying view of Bear

Photograph by the Author.

FIG. 122. BEAR ISLAND, OFF THE MAINLAND OF EASTERN LABRADOR; ILLUSTRATING THE WASHING AWAY OF SUCH PEPPERED BOULDERS AS THOSE SHOWN IN FIG. 121, BY THE OCEAN WAVES WHEN LABRADOR STOOD LOWER THAN NOW. THE BLACK ROCKS ARE IGNEOUS DIKES DUE TO INTRUSIONS OF MOLTEN MAGMA.

Island, which is about 100 feet high (Figure 122). The beaches, successively formed in steps as the land rose, are illustrated by Figure 123. Many of the boulders have been dragged down to low-tide level, where they now form long walls, high though almost submerged, and dangerous to small boats that attempt to land.

We measure the minimum uplift, at any point along the shore, by observing the difference between present sea-level and the sea-level near the close of the Glacial period. The position of the late-Glacial sea-level is given by the level of the lowest boulders left undisturbed by the ocean waves.

Using this method, six years ago, I was able to measure the uplift of Newfoundland since the ice melted from its surface.

On the map, Figure 124, we note a broken line, marked with two zeros. Along this line approximately, there has been no movement of the crust. The uplift was entirely to the north of the line. The figures give the number of feet of uplift, which steadily in-

Photograph by the Author.

FIG. 123. RAISED BOULDER BEACH NEAR SLOOP HARBOR, LABRADOR. SOME OF THE WELL ROUNDED BOULDERS ARE MORE THAN A FOOT IN DIAMETER. THE TOP OF THE BEACH IS ABOUT 180 FEET ABOVE SEA LEVEL; THE FOOT OF THE BEACH, ABOUT 40 FEET LOWER.

creases northward, until it amounts to 500 feet at the Strait of Belle Isle. Still farther to the northwest, the amount of the uplift continues to increase, so that at Hudson Bay it is as much as 1,250 feet or more.

This, then, is an excellent example of recent crustal warping.

The principle is so important that the reader may profitably study other photographs of the raised beaches, which have been placed high and dry by the slow uplift of the earth's crust when a heavy ice-cap was removed. European examples are chosen.

In every case these will demonstrate uplift, slow recoil, of the earth's crust.

Figure 125 is a view I snapped one summer day of 1897 on an island in the Gulf of Finland. This beach, more than 200 feet above the sea-level, is being slowly invaded by the forest.

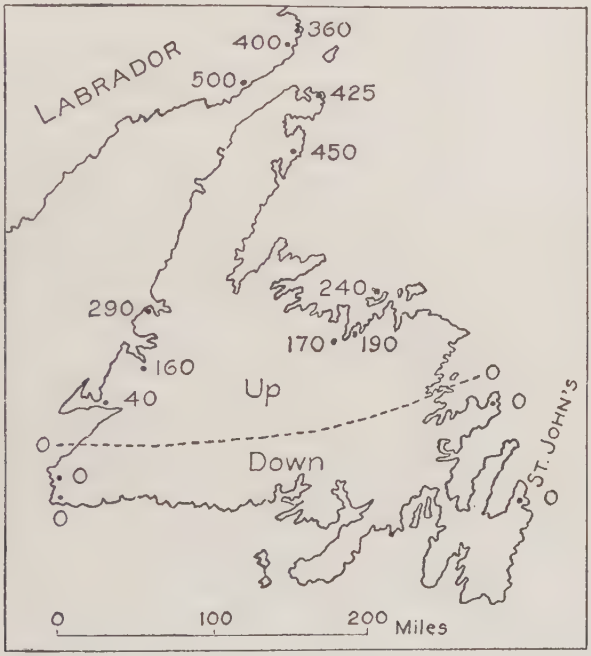


FIG. 124. MAP SHOWING THE POST-GLACIAL WARPING OF NEWFOUNDLAND. THE ZEROS REPRESENT PROVED FAILURE OF UPLIFT. THE NORTHERN PART HAS RISEN, BY AMOUNTS SHOWN IN FEET BY THE NUMBERS. THE AXIS OF WARPING IS AT THE BROKEN LINE.

The beach is at least 10,000 years old, but seedlings have a hard time to take hold.

The beach of the next view, photographed in Scotland (Figure 126), is 34 feet above sea-level. In the background we observe the old cliff, cut back on the hard rock by the thundering breakers of the North Atlantic a few thousand years ago.

The fine sea-cave shown in Figure 127 is a feature of the elevated 25-foot beach of Scotland.

Finally, we have a view of the conspicuous 100-foot rock bench of western Scotland, the highest well-marked strand of the region (Figure 128).

The uplift of the glaciated tract of northwestern Europe was

Photograph by the Author.

FIG. 125. A BOULDER BEACH ON THE ISLAND OF HOGLAND, GULF OF FINLAND. THIS IS A SEA BEACH NOW NEARLY 200 FEET ABOVE SEA-LEVEL, BECAUSE OF THE POST-GLACIAL UPLIFT OF THE REGION.

slow at first, then accelerated, and slowed down again. Apparently it is not yet quite finished, as indicated by the present rate of warping of the Baltic area, already described (Figure 117, page 186).

What was the mechanism of the uplift? We remember that under the ice-load the crust was depressed or basined. This basin

persisted long after the ice disappeared. Such persistence shows the crustal basining not to have been due merely to elastic compression of the weighted sector of the earth. Because, if the depression were a purely elastic effect, the rebound would have been practically simultaneous with the removal of the load of ice.

Photograph from the Scottish Geological Survey.

FIG. 126. ROCK BENCH CUT BY THE OCEAN WAVES IN SLATES AND LIMESTONE ON THE ISLAND OF LUING, ARGYLLSHIRE, SCOTLAND. THE BENCH IS 34 FEET ABOVE SEA-LEVEL, IN PART AT LEAST BECAUSE OF THE POST-GLACIAL UPLIFT OF THE REGION.

The long lag in the uplift of Scandinavia, on the other hand, can only mean that material had actually flowed out from beneath the glaciated tract.

The mechanism of uplift may be explained by the use of a series of diagrams (Figure 129). Section No. 1 represents the level surface of the ground before the ice-cap was formed. Section No. 2 shows again how the crust was basined under the load of ice. Arrows indicate the tendency to displacement of the crust. The deep-seated material in the earth flowed away laterally as the loaded region was punched down into the earth's

body. This plastic movement was probably accompanied by the formation of a very low, broad, viscous bulge of the ground all around the ice-cap. Note the bulge marked on each side; its relative height is much exaggerated in the drawing.

Photograph from the Scottish Geological Survey.

FIG. 127. SEA CAVE IN CLIFF AT THE EDGE OF THE 25-FOOT RAISED BEACH; WEST COAST OF THE ISLAND OF JURA, ARGYLLSHIRE.

Now imagine the ice to melt away. By exactly the same principle as that already described, the first reaction is an elastic rise of the whole region, including not only the basin where the load of ice had been, but also the ring of bulged ground all around the basin. This stage is shown by section No. 3. In the course of time, however, the rigidity of the earth shells breaks down. It breaks down because the shells are now being steadily and long stressed or pressed in the vertical direction, as indicated by the arrows of section No. 4. We see that, owing to the removal of the weight of the ice-cap, the bottom of the basin

tends to be squeezed up again. We see also that the weight of the super-elevated ring tends to cause it to subside. Both tendencies are ultimately satisfied by the up-punching of the basin, accompanied by a snapping-down of the surrounding ground.

Photograph from the Scottish Geological Survey.

FIG. 128. GRAVEL OF THE 100-FOOT RAISED BEACH, WEST COAST OF THE ISLAND OF JURA.

In the course of time, therefore, the crust comes back to its original level, as in section No. 5.

We may now turn from diagrams to the actual facts, selecting the Baltic area once more for illustration. The lines of equal post-Glacial uplift show where Scandinavia was basined under its load of ice during the Glacial period (Figure 119, page 189). Just outside the line of no post-Glacial uplift, the country was temporarily elevated higher than now, through the elastic reaction described, by the amount of at least 100 feet. Thus, southern Denmark and northern Germany were too high for

final equilibrium. So also the floor of the North Sea was considerably higher than now.

When, however, the long delay in the uplift of Scandinavia came to an end, the super-elevated part of the crust slowly subsided. The great central basin was annulled by the *upward*

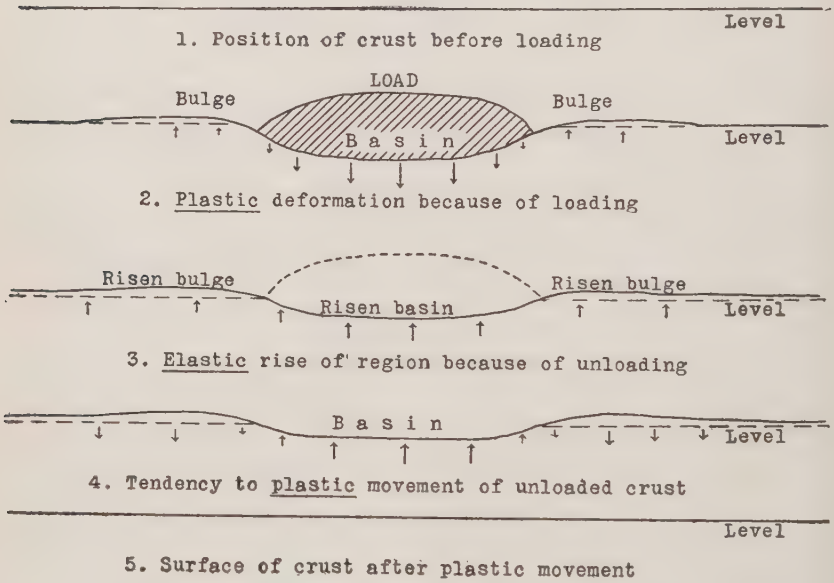


FIG. 129. SERIES OF CROSS-SECTIONS ILLUSTRATING THE DEFORMATION OF THE GROUND BY A GLACIAL LOAD, FOLLOWED BY DEFORMATION IN THE REVERSE SENSE AFTER THE ICE-CAP HAS MELTED. HEIGHTS AND DEPTHS ARE GREATLY EXAGGERATED.

punching of the earth shells beneath. That is, their rigidity broke down, and therewith vanished the condition for the continued super-elevation of southern Denmark, northern Germany, and the floor of the North Sea, regions which have "snapped down" nearly to their original, pre-Glacial positions. Accordingly, old forests, peat-bogs, beach deposits, and even human remains are found in borings in the ground of Denmark and northern Germany; similar formations have been dredged up from the bottom of the North Sea. These adjustments of the earth's crust,

though nearly complete, are still going on, as illustrated by the map of the contemporaneous warping of Scandinavia (Figure 117, page 186).

In a similar way, since the North American ice-cap disappeared, the belt of ground immediately surrounding the Labrador ice-cap has apparently sunk, simultaneously with the rise of Labrador, Quebec, northern New England, and other parts of the formerly basined region. For some thousands of years after the last ice melted, the glaciated tract was held hundreds of feet below its present level. In consequence, the Atlantic sent a long arm into Lake Ontario, another up the Ottawa valley, a third into the Champlain valley, and a fourth up the Hudson valley beyond Albany. New England was nearly, if not quite, an island, not many thousands of years ago. Arctic fishes and seals have left their bones in the muds which were laid down on the floors of these temporary inlets of salt water.

The associated elastic rise of the peripheral, slightly bulged ground seems to have been great enough to bring the sea bottom off Cape Cod up to the light of day; so that, a few thousands of years ago, a more or less continuous plain of marine sand and mud stretched its length from New York City to Nova Scotia.

Even two swallows do not make a summer. It is important to note that the earth has responded to a surface load of ice at a half-dozen places other than these mentioned, namely, northwestern Europe and northeastern North America. During the Glacial period there were independent ice-caps also on Greenland, thicker than the present glacier; on Spitzbergen; on British Columbia; on Patagonia; and on Antarctica, where again the ice was thicker than now. In all these cases the crust was basined under the former loads of ice and has slowly been uplifted hundreds of feet, in the effort to get back to equilibrium. Each is a case where nature has made a kind of experiment for our instruction.

Thus, when any extensive load of ice is placed on the earth's crust, the earth behaves systematically. The crust sinks under the load. Again, when such loads are removed, the crust rises

again. In either case, the distortion of the solid globe is largely plastic, but also partly elastic.

With these colossal experiments of nature in mind, we are better prepared to understand the even greater distortions which

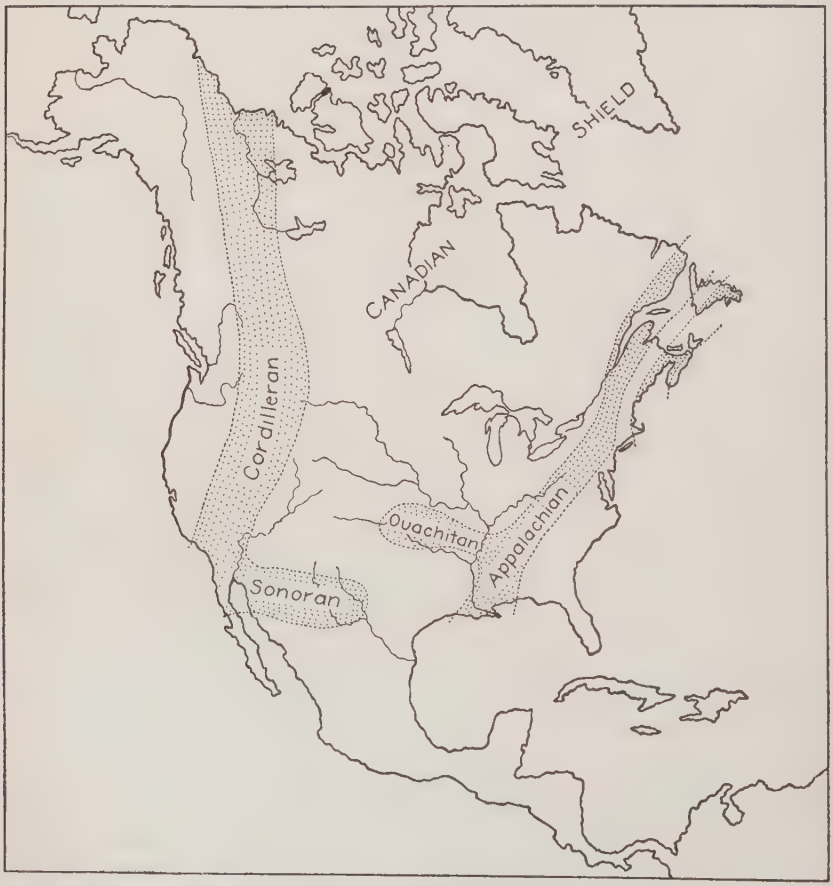


FIG. 130. MAP SHOWING THE BELTS WHERE NORTH AMERICA WAS LONG DOWN-WARPED, WITH THE FORMATION OF ELONGATED TROUGHS OR GEOSYNCLINES. (After Schuchert, with Slight Modification.)

have affected whole continents during geological time, long before the Glacial period, and quite without relation to loading by ice.

First, we shall consider briefly the important effect of surface loading due to the erosion of the continents.

Every moment of day and night the rivers are carrying mud and sand from the lands to the ocean floor. By slow weathering the firm rocks are broken up. About one-third of their substance is dissolved by the rain-water and carried, in solution, to the sea. The other two-thirds will ultimately be washed away by running water, or blown away by the wind. However, much of this solid detritus does not get as far as the main ocean. During past ages the continents have been so deformed that long basins, or belts of low ground, covered with shallow seas, have been formed inside the continental borders. The cause for the *initiation* of such basins is another problem which we shall not touch for the present; we shall merely accept the existence of the basins.

The basins have naturally trapped the river sediments on a grand scale. By the waves and currents of the shallow transgressing seas, these sediments have been distributed over the broad depressed belts.

Many of the depressed belts or troughs were extensive. Some were more than 1,000 miles long and several hundreds of miles wide. Figure 130 is a map showing where North America was thus locally basined or warped. The stippled belts inside the present coast-line were broad areas of prolonged deposition of sediments. The blank areas represent the lands then being eroded. From those lands the sand and mud, collecting within the troughs, were derived.

Since the sides of each trough slope gently inward, the form of the trough is called technically a syncline. The word "syncline" comes from the Greek, and means, literally, "sloping together." Because these particular troughs are very large, on an "earth" scale, they are also called "geosynclines."

The positions of principal geosynclines of North America are given on the map. Long ago, during the so-called Paleozoic Era of the earth's history, the site of the Appalachian Mountains was occupied by a long basin or trough or geosyncline, indicated (by stippling) on the eastern side of the continent. The Appalachian trough was continuous with the Ouachitan geosyncline of the Arkansas region. Similarly, the Rocky Mountains chain

now occupies the site of another great geosyncline, on the western side of the continent. This Cordilleran trough was continued into the belt marked "Sonoran" on the map. The lands being

Photograph by the Author.

FIG. 131. RIPPLE-MARKS ON HARD SANDSTONE (QUARTZITE) BEDS AT THE SUMMIT OF THE SELKIRK MOUNTAINS, 7,000 FEET ABOVE SEA-LEVEL. THE STRATA HAVE THERE BEEN UPTURNED INTO A NEARLY VERTICAL POSITION. THE HAMMER IS TWO FEET LONG.

worn down to supply the detrital fillings of these troughs are shown in blank.

The slow washing of sand, mud, and gravel into a geosyncline ultimately puts a considerable load on the down-warped crust. The added weight acts like the ice-loads, just described. The floor of the trough sinks, perpetuating the trough form in spite of the addition of layers of sediment. Consequently, inwash of still other detritus is invited. As a rule, during the geological past, the sinking of the floor of each trough nicely kept pace with the loading. The thin film of sea water covering the trough persisted, and yet never grew deep. Hence, such shallow-water

features as ripple marks were impressed on the layers of sediment through thicknesses of thousands of feet together (Figure 131).

The addition of new strata of sediment and the deepening of the troughs went on, until in some cases 10,000 to 50,000 feet of strata were accumulated. Each mass of sediment finally at-

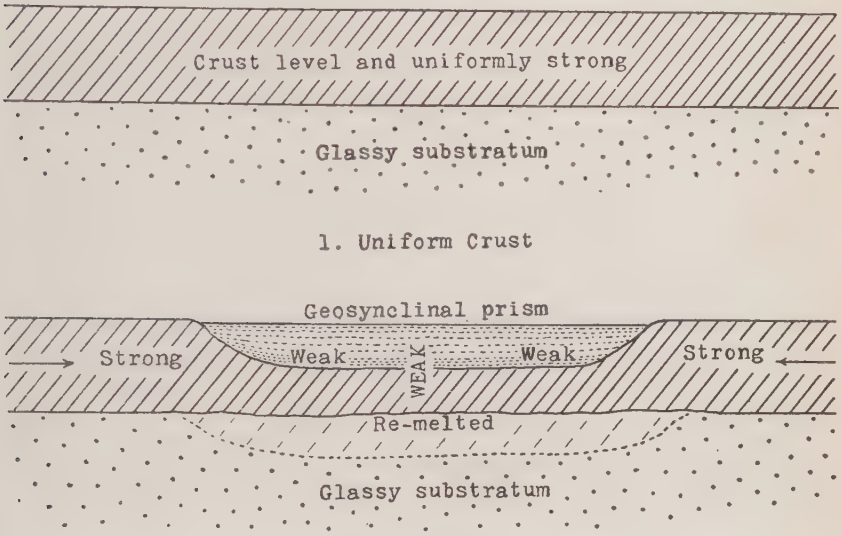


FIG. 132. CROSS-SECTIONS ILLUSTRATING DIAGRAMMATICALLY THE CONTRAST IN STRENGTH BETWEEN A UNIFORM CRUST OF NORMAL COMPOSITION AND THE CRUST WHERE LOCALLY WEAKENED BY A GEOSYNCLINAL PRISM OF SEDIMENTARY ROCKS. AS DRAWN, THE PRISM IS MORE SYMMETRICAL THAN THE ACTUAL PRISMS OF NATURE.

tained the form of a huge, elongated lens or prism, which was nearly flat above and convex below. The whole mass of sediment may be called, for convenience, a *geosynclinal prism*. A diagrammatic section through one of them is given in Figure 132. Section No. 1 shows by shading the normal crust resting on the hot, glassy substratum (dotted). Section No. 2 shows the very thick geosynclinal prism of weak sands, muds, and gravels, filling a basin of the down-warped crust. As the sediments slowly accumulated, the original crust sank under the load to deeper levels, where the earth's internal heat melted the lower part of

the former crust. This is indicated by the part of the cross-section marked "remelted." At the geosyncline the strong crust has been replaced by a distinctly weaker crust. It is at such weakened belts of the crust that mountain ranges are formed, as we shall note in the seventh chapter.

That chapter will also be concerned with the cause for the initiation and location of geosynclines, and with the cause for the building of mountains. I shall offer the suggestion that a leading condition for these momentous phases of the earth's distortion is the compressibility of the earth. The broad warping, broad distortion of the globe, preliminary to mountain-building, seems to be explained by three co-operating causes: first, the earth's contraction as it slowly cools; second, the slow lessening of the earth's rate of spin on its axis; third, the erosion of the continents, a process which, like the other two, has also continued through the geological ages. Each of these causes for the bodily distortion of the solid globe on a great scale can be better understood from our knowledge of the behavior of the earth's body under extensive loads of ice. That is a principal reason for present emphasis on the events of Glacial and post-Glacial time.

The distortion of the globe by the three other processes mentioned is an involved problem, a problem so complex that one may easily go astray while attempting to trace the chain of causation. However, there is no question as to the solid, proved *fact* that during geological time the earth has been systematically distorted; that is, its crust has been broadly warped out of its original level. We can use the fact even if its explanation be difficult.

Illustrations of the earth's distortion on a continental scale have already been given in a series of maps of North America at certain epochs of geological time (Figures 104–107 and 130). The whole story of our continent's warping would demand an indefinitely large number of such maps. In fact, North America has been like a very slow moving-picture, always changing since the remote infancy of the continent. The maximum transgression of the sea upon the back of the continent was probably that of

the Silurian period, which elapsed between the Cambrian period (Figure 107) and the Mississippian period (Figure 106). Even during the Silurian period, however, extensive areas of northeastern Canada and of Greenland remained land. Figures 104–107, 130, and 153 illustrate the tendency for the northeastern part of the

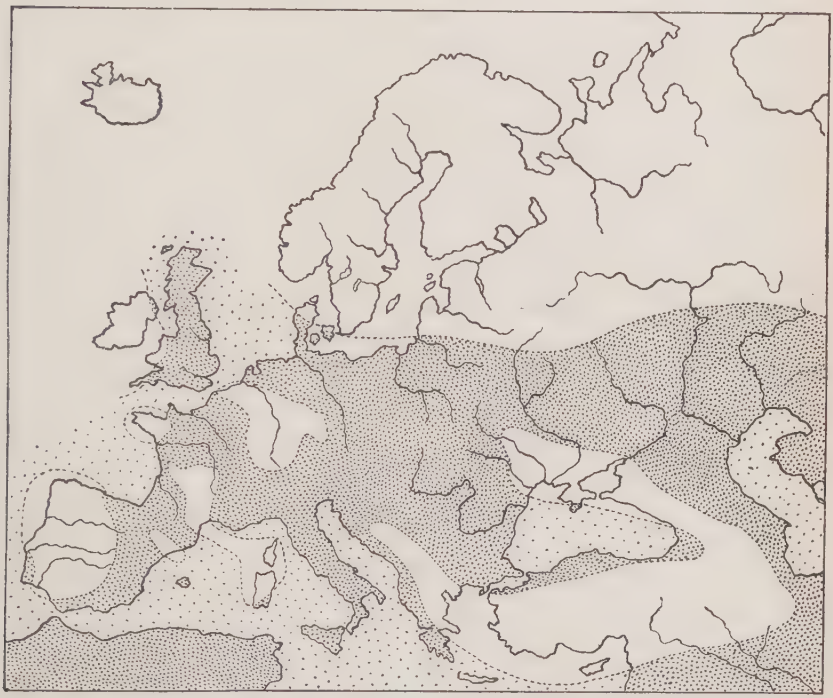


FIG. 133. EUROPE AT AN EPOCH OF THE CRETACEOUS PERIOD. THE STIPPLED AREAS WERE COVERED WITH A THIN VENEER OF SEA WATER. (After De Lapparent, in his "Traité de Géologie," Masson et Cie, Paris.)

continental surface to stand above sea-level. The importance of that fact will be emphasized in following pages. The warping of North America has been complex, but the fact mentioned is one of the constant features in the moving picture with its majestic rhythm. At this end of the "reel," the continental block stands nearly at its highest, with a minimum of transgressing or "shelf" sea.

On the other hand, the southern half of North America has tended to stand low through most of geological time. The Rocky Mountain geosyncline long persisted. It received detritus, which was washed down from the adjacent lands. Northeastern Canada and Greenland were eroded more or less steadily; much of the resulting detritus was carried southward by the ancient rivers and then spread by waves and currents of the shallow seas, which so largely covered the area of the United States.

The same kind of story could be told of every other continent. Europe is another moving-picture of the kind. Only one example of its many stages of warping will be given. Figure 133 shows Europe at an epoch of the Cretaceous period. We recognize the present shore-lines of ocean and seas. The stippled areas are those which were covered with the shallow transgressing sea of the Cretaceous epoch. Where the dots of the stippling are widely spaced, the Cretaceous sea covered regions which to-day are also covered with sea water. As in the case of North America, the northern part of the continent stood relatively high; the southern part relatively low.

Figure 153 of the next chapter (page 243) is a diagrammatic map of the world, suggesting a general tendency that governed the warping of the whole globe throughout the greater part of geological time. In spite of the infinite complexity of the forces which played on the earth's body during æons of time, this general tendency led to a rather systematic distortion of the planet. The significance of the distortion for the theory of the formation of mountain chains will be a leading topic of the following chapters.

Summary

We briefly review the subjects of this chapter. We have illustrated some of the geographical changes of the long past. We have sketched a few of the more important facts showing the mobility of even the solid, rocky crust of the earth with respect to sea-level. The sea-level itself has simultaneously shifted up and down, all over the globe. Each time, the world-wide rise

or sinking of that level has been very nearly or quite uniform. One of the causes for these remarkable swellings and shrinkings of the ocean's volume, and one cause only, has been emphasized. That cause is change in the volume of continental glaciers. When the glaciers increased, water was evaporated from the ocean and piled up as ice on the land; sea-level had to fall, everywhere. When continental glaciers melted and ice-water ran down to the ocean, sea-level had to rise, everywhere.

Hence, some notable changes in the positions of coast-lines and in the relations of land and sea were connected with the last Glacial period.

But, besides geographical changes due to world-wide rise or fall of sea-level, our globe has witnessed important geographical changes which were caused by slow warpings of the earth's crust. Though the continents, through geological time, have stood at least 10,000 feet above the sea bottom, yet some parts of the continental surfaces have sunk enough hundreds of feet to permit the sea to transgress those parts of the continental plateau. Other parts have been elevated, up-warped, many hundreds of feet. All of this movement was without the formation of mountains. What are the causes for these temporary floodings of the continental plateaus by shallow transgressing seas? What are the causes for the likewise slow retreat of the waters?

Few questions in geology are more difficult to answer, and yet we have found that much has recently been learned from the behavior of the earth's body under extensive loads of ice. We have seen that under such a load the earth, apparently so rigid, yields plastically. The plastic flow of the earth's materials occurs at great depth. Above the deep level of flow, the material of the globe is compressed, condensed, by the weight of the load. Hence, the loaded part of the crust is depressed elastically as well as plastically. When the ice melts away, the earth is distorted in just the opposite way; the area thus unloaded rises, and the movement is again both plastic and elastic.

Using the principles learned from the crustal warping connected with the great glaciers of the last Ice period, I have stated

the problem of continental warping on a still larger scale, and have presented some illustrations. The last two chapters of this book include the suggestion that mountain structures have been formed because the continents were broadly warped in past ages.

CHAPTER VI

MOUNTAIN RANGES

THE average rigidity of the earth is twice that of highly tempered steel. When struck a sudden blow, it rings like a bell. Particles, disturbed by the blow, vibrate for a time and finally come to rest in their original positions. This kind of mobility of the earth's materials is illustrated in earthquakes.

The earth's crust averages about 40 miles in thickness. It is an interlocking mass of innumerable crystals. Like each crystal, the rock layer as a whole shows a degree of permanent resistance to distortion, even under prolonged pressure or stress. The crust is a true solid, and relatively strong.

Beneath the crust is the substratum, a thick shell of hot basaltic glass. Against the disturbing influence of an earthquake the upper part of the substratum exhibits nearly one-half the rigidity of steel, but its resistance to prolonged distorting pressure breaks down with the passage of time. The hot glass under great pressure acts a good deal like pitch. One can make a tuning-fork out of pitch. Its twanging proves the pitch to be a stiff solid, as it reacts to a stress enduring only for a small fraction of a second. Yet the same tuning-fork will flow under its own weight. In some days or weeks you find it a flat cake, sprawling on the table. So it is with the substratum. Its strength, or ability to support a load permanently, is very low, approaching zero.

Because the temperature increases with depth below the surface, the decay of rigidity is probably the more rapid as the depth increases.

Under certain conditions, the basalt of the substratum loses its rigidity to such an extent that it is erupted into, and through, the crust; it flows like a liquid. We have studied this second phase of the earth's mobility, the basis of volcanic action.

There is a third kind of mobility. The shells of our onion-like earth have elasticity of volume; they are somewhat compressible under a weight. The loading of a sector of the earth causes that sector to contract toward the earth's center. The unloading of a sector causes it to expand vertically, away from the earth's center. Under the play of various forces, some sectors have thus contracted during geological time; they have contracted vertically; that is, along the radius of the globe. Other sectors have expanded vertically during geological time. Hence the crust, passively resting on the deeper, contracting or expanding sectors, has been warped. The crust has departed from the form of the ideal sea-level, a spheroidal form. During geological time, therefore, the surface of the solid earth has been slowly deformed; broad regions of higher, gently sloping ground have come to alternate with broad regions of low, gently sloping ground. The last chapter touched upon this third kind of mobility in the globe.

We are now to consider a fourth kind of mobility, a much more drastic distortion of the solid crust of the earth: that represented in mountains and mountain chains. The crust is strong, but its strength has not prevented its having been broken, crumpled, mashed together. The results of such intense local distortion are mountain structure and ultimately mountain form.

The present chapter will sketch the leading characteristics of the world's mountains. In this way the ground will be prepared for the next chapter, which will specially discuss the origin of the forces responsible for the paroxysms of mountain-building; that is, we shall then be concerned with the cause of the making of mountains. Now a very important clue to the origin of the forces is found in the distribution of ordinary mountain chains. The chains do not occur indiscriminately, all over the globe. They are confined to certain belts or zones. Along those zones the mountain-making forces worked their will. Attentive study of location will guide us toward the solution of the problem of origin. Additional light comes from a study of the internal structure of mountains, as well as from study of their form.

Further, thought about the origin of mountains must be controlled by the fact that mountain ranges are not all of the same age. The process of mountain-building did not go on uninterruptedly through geological time; but, on the other hand, its effects were concentrated in certain epochs of earth-history,

FIG. 134. AXIAL TRENDS OF THE ALPINE AND RELATED RANGES OF MOUNTAINS IN EUROPE. (After Staub.)

epochs separated by very long periods, during which the earth's crust was relatively at ease and nowhere roughly handled by the forces of nature. So we are to think of the location, internal structure, form, and relative age of each principal mountain chain.

As children in school, we learned to make maps of the high, rugged mountains, the first kind to be reviewed. We drew caterpillars to represent Rockies, Andes, Alps, and the like. We learned the individual ranges by name. We did not learn that these troubling but useful names tended to obscure the comparatively simple system into which most ranges fall. Still less did we appre-

ciate the fact that all these rugged mountains we caterpillared are, figuratively and literally, upstarts—recent, new features of the old earth. To understand the system one needs to note the positions of the ranges in both space and time.

First, let us glance at the world map, beginning with Europe's most westerly chain, the Pyrenees (Figure 134). On the west the Pyrenees drop off abruptly into Atlantic water; the eastern end of the range drops off abruptly into the Mediterranean. The geologist has found, however, that the mountain structure and form used to extend, above sea-level, farther to the westward and farther to the eastward. Where once were high mountains there is now deep water. The original Pyrenees were unstable, and to east and west have sunk below sea-level.

At once, then, we see that our school-day caterpillar did not tell the whole story. The essential thing, the complex Pyrenees structure, is partly submarine. This unit, this individual member of the earth's crust, is different from, greater than, the visible, lofty, rugged chain of our school geographies.

The Pyrenees really continue under the Mediterranean toward the Rivieran Alps, where again high mountains rise abruptly from deep water, the site of more drowning.

The Jura Mountains, though nearly separated from the Alps by lower ground, originated during the same geological period and under the same set of forces. We used to draw one caterpillar for the Alps and another for the long, beautiful curve of the Carpathian chain. Yet the geologist finds that one caterpillar does for both. The Alpine highland is nearly continuous with the Carpathian highland; still more fundamental is the continuity of the Alpine structure with the Carpathian structure. Further, the Alpine-Carpathian structure continues into the curving chain of the Balkan peninsula. The Balkan chain is sharply cut off by the Black Sea basin, where the eastern end of the Balkan Mountains has been drowned in comparatively recent time, just as the western and eastern Pyrenees have been drowned.

In spite of the writhing of their axes, all these mountain ranges

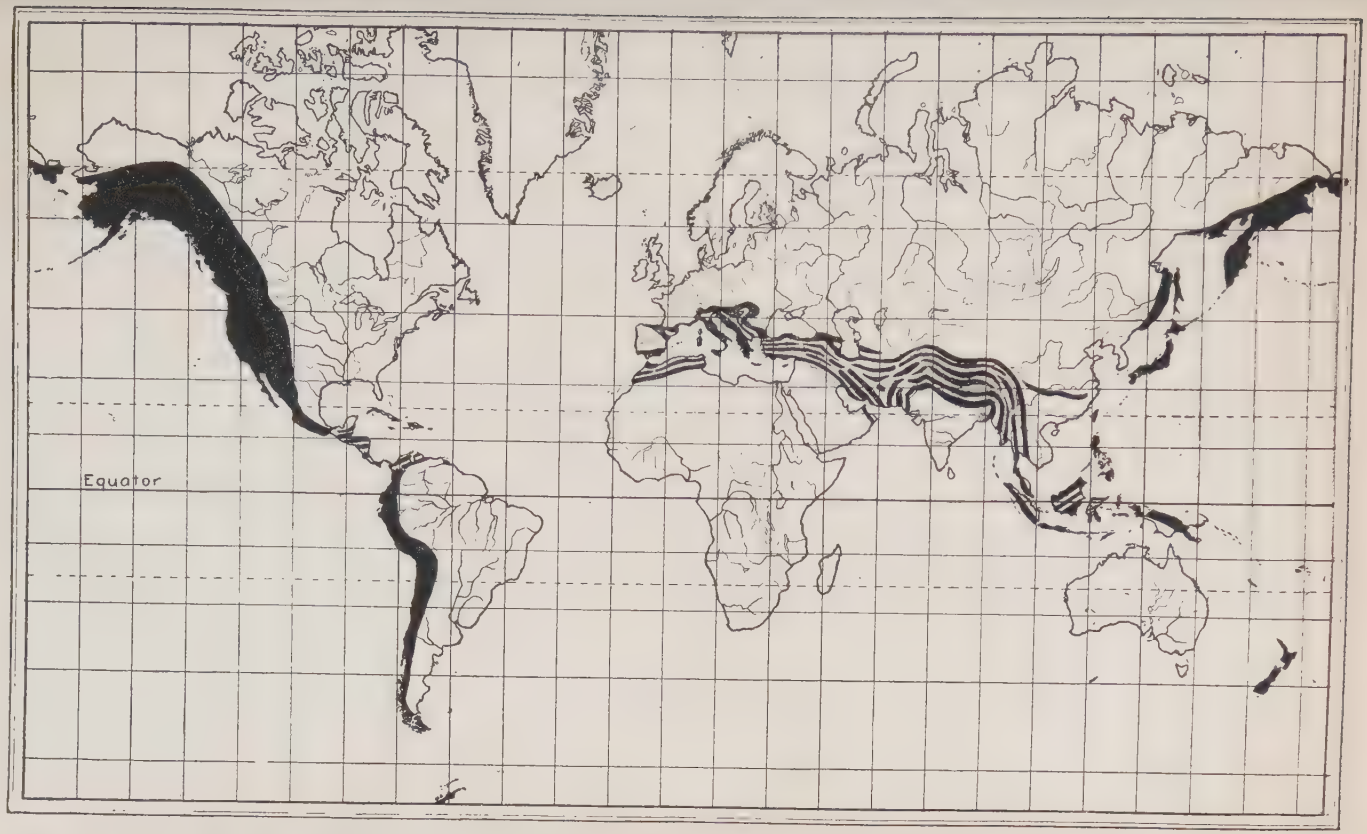


FIG. 135. MAP OF THE WORLD, SHOWING THE LOCATIONS OF THE CHIEF HIGH, YOUNG, AND RUGGED CHAINS OF MOUNTAINS. MERCATOR'S PROJECTION. (BASE COPIED FROM THE J. P. GOODE MODEL, UNIVERSITY OF CHICAGO PRESS.)

of southern Europe may be regarded as an east-west system. Into the same east-west system we may put the Atlas Mountains of northern Africa, the so-called Dinaride group (including the Apennines of Italy, and the broad, tangled belt from the Tyrol to Greece), the Tauride Mountains of Asia Minor, the Iranide

FIG. 136. MAP SUGGESTING, BY THE TRENDS OF THE DRY LANDS AND BY THE CONTOURS OF THE OCEAN BOTTOM (ISOBATHS, DEPTHS IN METERS), THE PROLONGATION OF THE STRUCTURE OF THE ANDES INTO WEST ANTARCTICA. (FROM WEGENER'S "ORIGIN OF CONTINENTS AND OCEANS," E. P. DUTTON COMPANY, NEW YORK.)

group of Persia, the Himalaya of India, and some of the Chinese complex of mountains.

This Old World band of rugged mountains, 10,000 miles long, has been built well within the boundaries of the Eurasian continent. This mountain belt is in the midst of the land; it may be called appropriately the *Mediterranean Rugged Belt of Eurasia.*

Of closely similar structure and age are the mountains of the West Indies, southern Mexico, central Mexico, and northern Venezuela. These ranges together form a broad east-west system, lying between two major masses of land, North America

and South America; it is the *American Mediterranean Rugged Belt*.

Generalizing still further, we may think of both of these belts as constituting a single east-west, mediterranean rugged belt. It ranges from 10 degrees north latitude to about 45 degrees north latitude; so this huge group of mountains may be described as occupying a mid-latitude zone of the earth. In Figure 135 the belt is represented by narrow black bands, which are directed along the axial trends of the mountain chains.

A longer system of high mountains encircles the Pacific more or less completely. Our favorite caterpillar of school-days was the Andes, because of its simple relation to the simplest continent. In those days we did not bother with the fact that the Andes system fades into the east-west Antillean system of mountains, just mentioned. Nor did we realize the abrupt eastward turning of the Andean structure at Cape Horn into a long, sweeping curve through the island of South Georgia and back, westward, to West Antarctica. See Figure 136. Recent explorations show the Andean structure also in West Antarctica. The Andes of West Antarctica, if we may so describe its mountains for present emphasis, thus help to frame in the Pacific basin.

From southern Mexico to Alaska, our own Cordillera runs continuously along the North American coast, though locally drowned at the Gulf of California and at the Gulf of Georgia. A more extensive subsidence has drowned the Cordillera at Bering Sea, but a few mountain-tops, covered with volcanoes, are still visible as the Aleutian Islands. That curved line of depressed mountains impinges on Kamchatka, where the rugged mountain frame of the Pacific is once more continuous for a long stretch. Drowned on the south, it shows the tops of its many peaks in the Kurile Islands. Farther to the south the colossal zone of mountains rises above sea-level in the Japanese, Philippine, East Indian, Fijian, Tongan, and New Zealand islands.

From New Zealand to Antarctica is a thousand-mile break, where full information is lacking.

On the whole we see that the Pacific basin is rather definitely

framed by a single system of rugged mountains, 25,000 miles long. This system is largely submarine. In Figure 135 and Figure 170, page 283, the grand belt is shown in solid black, wherever the Circum-Pacific Mountains appear above sea-level. The reader will understand the Cordilleras of the two Americas and West Antarctica to extend out laterally some distance under the Pacific Ocean. The Circum-Pacific Belt, from Kamchatka to New Zealand, is not only continuous but likewise covers much more ground than appears merely from the areas marked with solid black.

While the design used in Figures 135, 169, and 170 for the axial trends of the east-west system of mountains continues to the Pacific, both in Central America and in the East Indies, the rock formations of each of these regions have also shared in the disturbances that made the Circum-Pacific chains.

Thus the rugged mountain ranges of the globe chiefly occur in two belts, the mid-latitude *Mediterranean Zone* and the *Circum-Pacific Zone*, with total length of 35,000 miles. The former contains Mount Everest, the highest mountain-top as measured above sea-level. The Circum-Pacific Zone contains the deepest mountain-top as measured below sea-level.

Outside of the two zones are other ranges, including the Appalachians, the Urals, the Cape Colony range, and others. These will be considered later. Meantime we shall look at the architecture of the rugged structures which we have already traced on the map.

Leonardo da Vinci heard thunder from the Vatican because he discovered shells of marine animals in the high mountains. The fundamentalists had received another shock. Ultimately they found that a molluscan cemetery could be perched at any height without involving the safety of true religion. Worshippers of the letter are still laboring under the delusion that Genesis is a text-book of geology, but even they are ready to concede the marine origin of strata, rock layers, visible in the cloud-capped towers. With such sanction the geologist has grown bold. He believes the evidence of his eyes, the validity of a yard-stick. He

has gone into the mountains and found them to be largely made up of sediments which were originally laid down under the sea. Moreover, he has found a rule obeyed by all the greater mountain ranges: each has been formed in belts on the earth where such sedimentation was prolonged, so that the total thickness of

Photograph from the Scottish Geological Survey.

FIG. 137. THIN-BEDDED FLAGSTONES OF HOLBORN HEAD, CAITHNESS.

sediments or strata at each place became very great. In maximum this thickness ranges from 20,000 to 50,000 feet.

Such an elongated mass of sediment we have learned to call a geosynclinal prism. A geosynclinal prism is the preliminary condition for the formation of any major mountain range. We have seen that each prism has been itself developed in consequence of prolonged down-warping of the earth's crust. So it was with both the Mediterranean and Circum-Pacific Zones of mountains. Each zone was long a place of geosynclinal sinking and of the thickening of sediments. Under their own weight, aided by the chemical activity of underground water and by

the heat of the earth's interior, these layered sediments became hardened. They became stratified rocks, like those illustrated in Figure 137, where the pictured layers of flagstones in Caithness, Scotland, lie flat; that is the typical attitude of geosynclinal strata before mountain-building begins.

Photograph by F. E. Wright.

FIG. 138. UPTURNED BEDS OF SANDSTONE AND SHALE AT GAMKA POORT, CAPE PROVINCE, SOUTH AFRICA.

Even the youngest mountain range is old enough to have been already trenched by rivers, which slowly but surely cut down into the rocks. Entering one of these valleys, we soon discover that the individual strata of the range have been systematically deformed; they are no longer level or nearly so. Figure 138 is a photograph of beds of sandstone that were tilted up through half a right angle during the building of the mountains of the Cape Province, South Africa.

Figure 139 illustrates how stratified rocks have been flexed into an arch, one of the simpler results of mountain-building

force. At many cross-sections of such folded rocks, the structures are seen to have been greatly eroded (Figure 140). Obviously the beds of rock used to extend upward, into the air; much of their substance has already been worn away by weather and rain-wash.

Other rock folds have suffered still more intense deformation;

FIG. 139. AN ANTICLINE IN STRATIFIED ROCKS OF ENGLAND.

arches and troughs have been tightly squeezed together, and the whole series of structures has been thrown over. The strata are often crumpled in detail (Figure 141).

In many cases a single mountain is an eroded remnant of rock beds which have been simply compressed into an open-trough structure.

The only way in which a succession of folds can be formed is by lateral compression of the strata. A paper-covered magazine may be folded by pressure applied to its back and front edges. During the folding the individual leaves of the book shear over one another; similarly the strata of a mountain range have been

sheared over one another. With energetic crumpling, each leaf of the magazine, like each stratum of rock, is plastically deformed. Stratified rocks at the earth's surface are brittle; even when deeply buried and thus confined, they are brittle if suddenly and greatly stressed. On the other hand, if a deforming force is

FIG. 140. MOUNT HEAVENS, MONTANA.

slowly applied, the strata at a little depth can yield without pronounced fracturing. Their materials are really plastic; the rocks flow as they are folded. Rocks are like human beings; they will bend before force, if you give them time enough and are not too rough with them. After a fold has been formed and thrown over, continued horizontal pressure is relieved by the slicing of the folded beds. These are broken across, along planes which are moderately inclined to the horizontal plane. Relatively, one block of rock moves over another block along the plane of scission or fracture. This kind of displacement of rock is called a *thrust.*

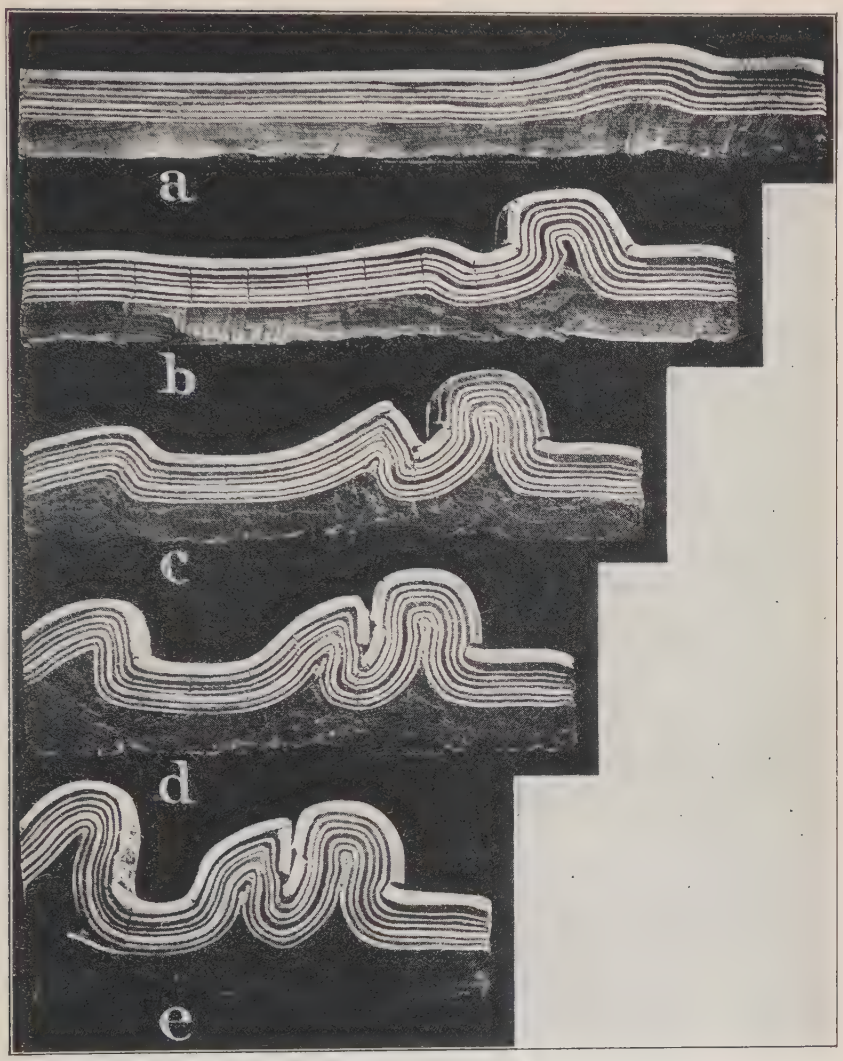
Nature's folds and thrusts can be imitated in the laboratory. An analogy to the folding is seen in the behavior of a metal ribbon pressed at each end. The ribbon becomes bent into the arch-and-trough form. If the ribbon is thinner toward one end, the bending there is naturally more pronounced.

Photograph from the Scottish Geological Survey.

FIG. 141. CRUMPLING OF LIMESTONE BEDS AT BOYNE BAY, BANFFSHIRE.

A metal is elastic. After the pressure at the ends is taken off, the ribbon is likely to fly back, more or less perfectly attaining its original flat shape. Not so with beds of rock. During their folding the material has actually flowed. After the folding the elastic recoil is very slight and quite insufficient to annul the new structure. The rock has a permanent set.

A closer experimental analogy to actual mountain-folding is therefore to be had if materials more plastic or moldable than steel or brass are used. Layers of clay, sand, plaster, and felt, representing rock strata, are suitable for the experiment. While weighted above by a thick bed of loose steel shot, those plastic



Photograph from the United States Geological Survey.

FIG. 142. EXPERIMENTS IMITATING THE FOLDS FOUND IN MOUNTAIN RANGES. (AFTER WILLIS.) NOTE THE PROGRESSIVE SHORTENING OF THE PILE OF STRATA.

layers are laterally compressed. The effect is to give excellent imitations of rock folds and thrusts.

The top section, *a*, of Figure 142 illustrates such experimental folding in the incipient stage. The next section, *b*, shows

how the initial arch and trough have been accentuated by additional pressure from the ends of the pile of beds. We can see from the diminished width of the section from left to right, how much additional compression there has been. The other sections illustrate further stages of the deformation, which at last

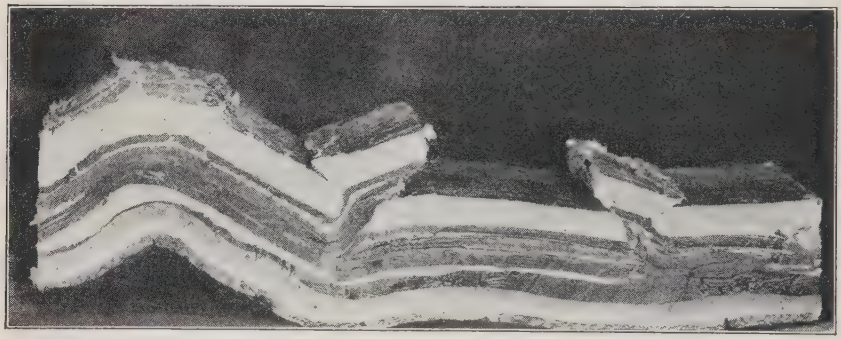


FIG. 143. EXPERIMENT BY JAGGAR, IMITATING THE THRUSTS FOUND IN MOUNTAIN RANGES.

leads to more or less tight closing of the folds, anticlines and synclines, as they are called in geology.

Another experiment (Figure 143) gives a parallel to the thrusts of nature. We see how the stronger, thick layer has been broken and locally driven over the underlying, flexed layers, which here again were originally horizontal.

Experiments help the imagination to understand the kinds of movement involved in mountain-building. They can not directly tell us the intensity of the force applied. Clearly, however, the force has been very great, for rocks are strong. Whence came the force? That is the supreme problem of mountain-building. Before attacking it, we shall do well to collect some more facts.

First, the fate of many a geosynclinal prism may be reviewed. Prolonged sedimentation has thickened the prism to a maximum depth of five or ten miles. Then, in some way or other, lateral, horizontal pressure is applied. The strata are folded into a series of arches and troughs, anticlines and synclines. Figures 144–5 represent sections and perspective views of a syncline and an

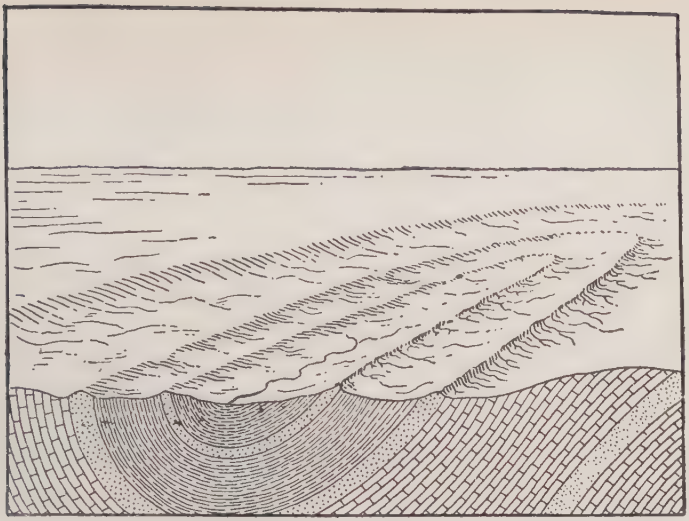


FIG. 144. CROSS-SECTION AND PERSPECTIVE VIEW OF AN ERODED SYNCLINE. (After Willis in "Geologic Structures," McGraw-Hill Book Company, New York.)

anticline respectively. Each structure is supposed to have been long eroded, so that the harder beds (dotted) stand up as mountain ridges, the softer beds (lined) underlying the valleys.

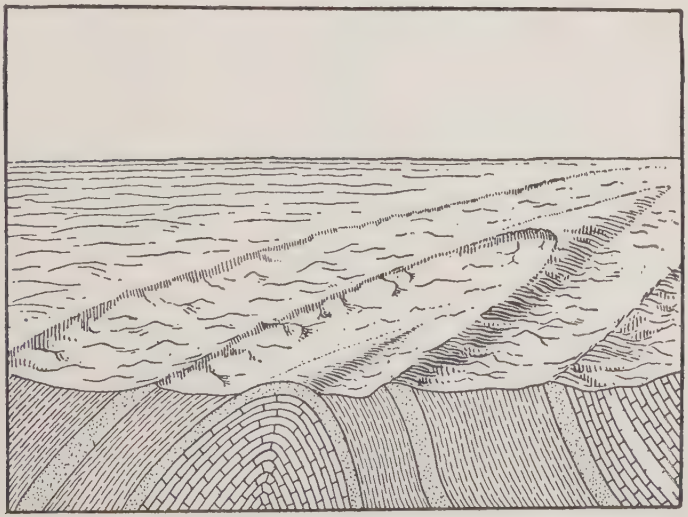


FIG. 145. CROSS-SECTION AND PERSPECTIVE VIEW OF AN ERODED ANTICLINE. (After Willis in "Geologic Structures," McGraw-Hill Book Company, New York.)

The Jura Mountains of France and Switzerland are classic examples of simply folded mountains. In the diagram of Figure 146 is seen the folded structure, clearly expressed in the section of the foreground. The wrinkling of the earth's surface and the

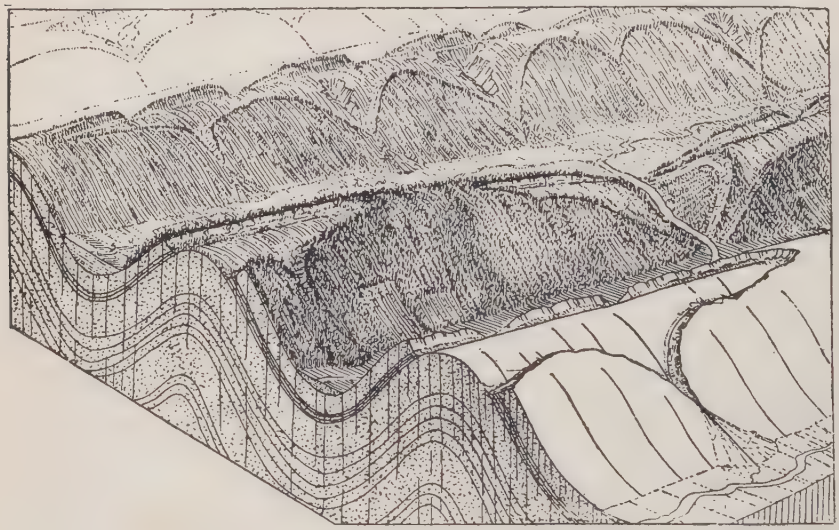


FIG. 146. DIAGRAM OF THE STRUCTURE AND RELIEF OF THE JURA MOUNTAINS. (After Davis in His "Physical Geography," Ginn and Company.)

effect of some erosion and valley-making are indicated in the perspective view of the mountains. More nearly representing a sample of the actual Jura Mountains is a map of a few of the anticlines and synclines (Figure 147). Their structure appears in the section across the folds.

Pennsylvania furnishes another example of relatively simple mountains, greatly eroded. The long ridges of the State are located on the edges of the beds, which are specially resistant to the weather and rain-washing, while the adjacent valleys are underlain by equally deformed but less resistant strata.

Still more imposing effects of horizontal compression are illustrated by the ranges showing dominant thrusts.

Chief Mountain, Montana, is a fine pile, standing several

thousand feet above the Great Plains (Figure 148). The mountain is a remnant of a thick, greatly eroded, dissected slice of old geosynclinal sediments. That slice had been thrust bodily up

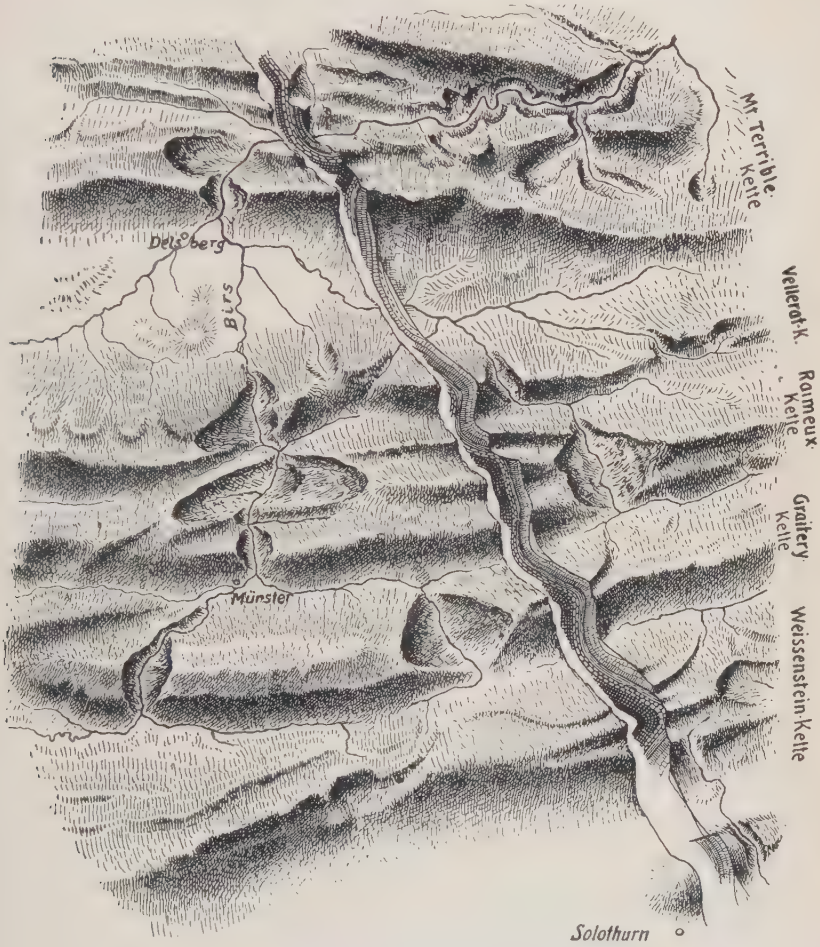
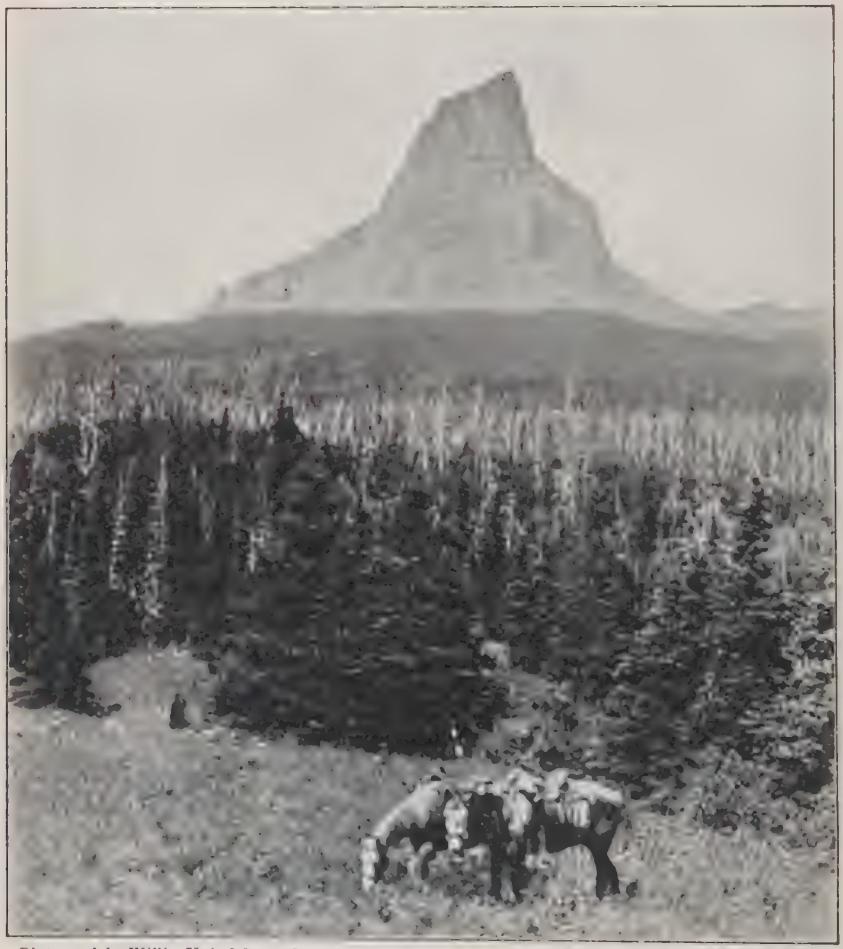


FIG. 147. MAP AND SECTION OF PART OF THE JURA RANGE.
(After Steinmann.)

on the much younger strata of the Great Plains, and then driven over them, eastward, for a distance of at least eight miles. Indeed, the thrust may have been several times eight miles. In the background of the photograph, we see the very ancient, gray-

tinted rocks of the mountain. The surface along which they were shoved is near the visible base of these old rocks. I have seen that surface. It is polished almost like a mirror; the polish-



Photograph by Willis, United States Geological Survey.

FIG. 148. THE OVERTHRUST MASS OF CHIEF MOUNTAIN, MONTANA.

ing was the effect of friction of the slowly moving slice of the earth's crust as it was driven over the much younger shaly rocks of the Plains. The forest-covered slope is underlain by these younger rocks, and the camera was pointed eastward, away from the Rocky Mountain Front, over the Great Plains province.

By similar thrusting, the whole Rocky Mountain Front, for hundreds of miles, has been pushed up and then out, many miles over the plains.

Northwestern Scotland is celebrated for overthrusts. In the accompanying picture (Figure 149), we see the actual outcrop

Photograph from the Scottish Geological Survey.

FIG. 149. LEWISIAN GNEISS THRUST OVER MUCH YOUNGER (CAMBRIAN) SANDSTONE; AT THE HEAD OF LOCH GLENCOUL, SUTHERLANDSHIRE.

of a plane of overthrust; that is, the interface along which the older rocks (on the left, with darker tint) have been shoved up and over younger rocks (those with light tint in the lower part of the cliff).

Figure 150 is a view of another Scottish thrust-plane, exposed by erosion. The block of rock on the right moved up, along the plane, now inclined and coincident with the steepish slope descending from left to right. The migrations of the overriding blocks of Scotland are measurable in miles.

Specially impressive is the overthrusting or rafting together

of the strata composing the European Alps. The kind of movement responsible for this famous range is illustrated by the series of cross-sections in Figure 151. The uppermost section is that of a series of strata which have been flexed out of their original horizontal position. Both the arch and the adjacent trough

Photograph from the Scottish Geological Survey.

FIG. 150. BARED SOLE OR SURFACE OF THRUST (MOINE THRUST PLANE); NEAR KNOCKAN, SUTHERLANDSHIRE.

have been overthrown toward the left. The mountain-building pressure continued. The strata, now so far deformed, are henceforth unable to yield by mere folding. The arch is torn away from the trough, riding over the latter, to the left. By successive steps, the overthrusting finally arrives at the stage represented by the lowest cross-section. Note the movement of a sample point on the overthrust slab of rock, such as that marked with a cross and the letter *a*.

During the building of the Alps gigantic slabs of rock, thousands of feet thick, hundreds of miles long, and tens of miles wide, were thrust up and then over, relatively to the rocks be-

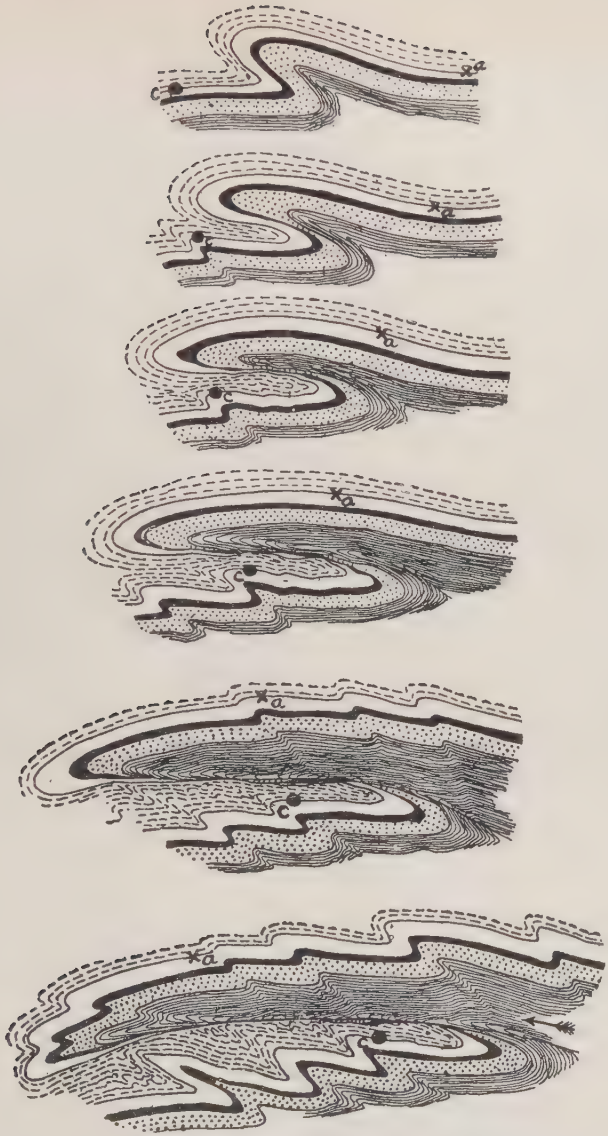


FIG. 151. CROSS-SECTIONS TO ILLUSTRATE PROGRESSIVE FOLDING, THRUSTING, AND CONSEQUENT LOCAL THICKENING OF A SERIES OF ROCK STRATA—TYPICAL ALPINE STRUCTURES. (After Leith in "Structural Geology," Henry Holt and Company, New York.)

neath. The direction of the relative overthrusting movement was from Africa toward the main mass of Europe on the north. The visible rocks of the northern Alps of Switzerland have thus been shoved northward distances of the order of 100 miles. In a sense the Alps used to be on the present site of northern Italy.

Having looked at cross-sections of mountain ranges, now let us look at their maps or ground-plans.

Overturned folds, as well as the thrusts of the Alps seen in section, show that the mountain strata have not yielded symmetrically under horizontal pressure. The mountain ranges have been built lopsided. The ground-plans of mountain chains tell the same story. In plan the Alps are not straight; they are bowed, strongly bent, away from Africa. On the map (Figure 134, page 213) we recognize the axial trend of the Alps, shown by a heavy black band. The ground-plan of the Carpathians is a bold curve, or arc, convex to the northeast, toward Russia.

The Himalaya of northern India is curved away from the main body of Asia (Figure 152). Back of the front range of the Himalaya is a series of concentric mountain arcs, roughly indicated on the map by lines. The whole series forms a festoon of arcs, convex toward peninsular India.

So it is with other members of the great Mediterranean Rugged Belt of mountains in Eurasia. From Spain to Roumania, the arcs tend to curve convexly toward the north, away from Africa, as if strong Africa had butted into weak Europe and crumpled its edge. From Roumania to China, the arcs tend to curve convexly toward the south, away from the principal mass of Eurasia, as if Eurasia had there been the active agent in the mountain-making.

The same asymmetry for the Circum-Pacific chains leaps to the eye in the case of the Aleutian and Japanese members of this other major zone. On the maps (Figure 135 and Figure 152), the emerged parts of the mountain ranges of Alaska, the Aleutian Islands, and Asia are shown in solid black or by axial lines. The asymmetry is perhaps less obvious elsewhere, but patient study by geologists has shown its reality. The Circum-Pacific

ranges are systematically curved in ground-plan, convexly toward the Pacific; they are concave toward their respective continents.

This grand feature of the world's high, rugged mountain chains suggests the kind of movement which has accompanied

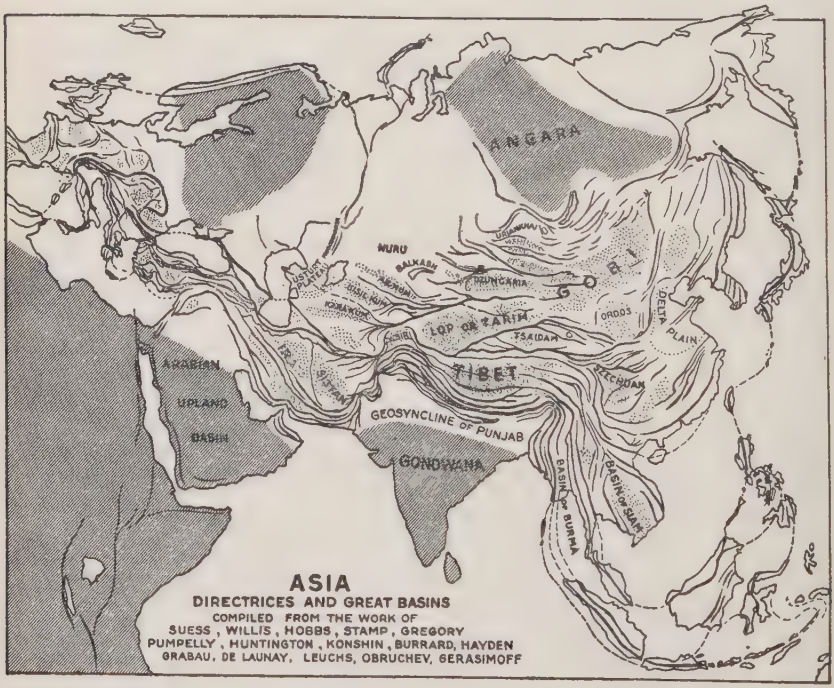


FIG. 152. MAP OF MOUNTAIN TRENDS IN ASIA. (After Berkey and Morris.)

their formation. The outer skin of the earth seems to have flowed viscously in the directions of the convexities of the mountain arcs; somewhat in the manner of pitch or tar, which festoons its surface with rolls as it slowly flows over a floor. The direction of each great crustal flow in the earth was, roughly speaking, in the direction of the arrow which would fit the bent bow of the mountain arc.

The garland or festoon form of the arcs adds another suggestion. The surface flow has affected not merely those parts

of the earth's skin which lie within the arcs. It rather appears as if a large part, or the whole, of a continent had moved. When it slowly migrated, it met special resistance at certain points, between which movement was less impeded. Thus the mountain ranges tend to be crowded together at the points of special resistance; and in the areas of greater mobility the garlands of the more widely spaced ranges were deployed. The Himalaya and ranges of Tibet form a typical garland, hung, as it were, on more resistant parts of the crust at the east and west ends of this grandest of all chains (Figure 152).

We now ask the question: Why are mountains high? Horizontal compression of the earth's crust in zones which had been heavily loaded with sediments is seen to be the dominant cause of mountain structure as represented in the existing high ranges. In books, both popular and technical, one finds lateral compression directly credited also with the great heights of these ranges. Good evidence is accumulating that this opinion is not warranted by the facts.

For example, after our western Cordillera underwent its last paroxysm of folding, its surface long stood much lower than now. The prolonged period of relatively low altitude was closed by uplift of the folded structure. Along with the crumpled rocks, the Arizona strata, which had escaped folding, were also lifted thousands of feet. Since then, and because of this uplift, the Colorado River has cut its deep canyon. Even the great depth of the canyon fails to measure the whole uplift of this part of the Cordilleran region. It is that later broad uplift which largely explains the present height of the Rocky Mountains and the ranges and plateaus to the west.

The same explanation applies to the relief of the Alps, Pyrenees, Himalaya, Andes, and apparently to all other lofty parts of the Mediterranean and Circum-Pacific zones.

Moreover, we have seen some of the long mountain arcs to be actually, in largest part, below sea-level. For example, Japan and the Philippine Islands are but the emerged tops of mountain chains of much greater respective lengths and areas than

either of these regions of dry land. Similarly with the West Indian and East Indian mountains. All of them are among the youngest ranges of the globe. They, like all others, were formed by down-folding and down-thrusting, the deformed rock *sinking* as it was folded, thrust, and rafted together. The mass of folded rocks sinks, because of its weight, into the weak body of the earth.

This newer conception of mountain formation has a considerable advantage. When one imitates mountain folds by lateral pressure on a magazine lying on a table, he can readily exert enough force to make an arch stand well above the table. This is true, because the weight of the arch is small. A mountain arch, or a series of mountain folds, or a pile of overthrust mountain blocks, is a very heavy thing. To lift it means a great piece of work. Work can be done only by the exertion of force. The higher a mountain block is raised, the more its weight tends to counterbalance the force available for the continuance of the mountain-building. In the next chapter we shall see reasons for believing that the mountain-building force has not been handicapped by having to give ranges lofty heights from the start. Why the major uplifts have occurred long after intense lateral compression ceased will be another topic of that chapter (page 277).

Meantime we accept the fact and briefly note an important consequence. The broad up-warping of the crust implies an immediate invigoration of the rivers flowing over the mountainous structure. So high have been the uplifts that powerful glaciers have been developed, and they too have attacked the structure. Already the Alpine structure has been much diminished by erosion, and thousands of valleys, gorges, and amphitheaters have been cut in the complex mass of rocks; so that to-day the Alps are really more valleys than mountains. The ruggedness of all the high ranges of the globe is due more to such recent dissection, erosion, than to the initial form of the ranges.

We pause a moment to summarize. The formation of one of the existing rugged ranges of mountains has had these stages:

First, preparation of a thick lens of sediment, a geosynclinal prism;

Second, lateral compression of the rocks of the geosynclinal belt, resulting in the development of the dominant *structures* of the range, the mountains being low or even submarine;

Third, after a long interval of time—millions of years—broad up-warping of the fold-thrust belt; hence high *elevation;*

Fourth, accelerated erosion; deep valleys cut; the individual mountains, the spectacular massifs of our own day, thus carved out of the complex structures; hence peaks, ridges, cliffs, *ruggedness.*

If left undisturbed by crustal movements, the future of each high range, now above sea-level, is clear. Every moment weather, rain, wind, and glacier are at work destroying the mass. The mountain teeth are high and strong, but they slowly yield to the elements. In the long future the teeth will be reduced by erosion to roots. Ultimately the mountain teeth will be worn down to the gums, so to speak. A flat lowland surface will be developed on the mountain complex.

The forecast is also retrospect. As a matter of fact, this very lowering of mountain pride has gone on, again and again, in the hoary past of geological time. The term "everlasting hills" has, again and again, proved incorrect. The globe bears many mountains so old that they now no longer can be barriers before railways, highways, or rivers. Some are so old that few of their inhabitants realize the true nature of the ground they live upon. It is not obvious that the city of Boston rests on the surface of one of the world's greatest mountain chains; yet it does. Probably some of the farmers who plough the fields of eastern Tennessee do not know that they are moving about on the top of an eroded mountain range of the first class.

Before the problem of mountain-building force can be fairly attacked, we should take a glance at the character and distribution of these older ranges also. Space fails for their full discussion; attention will be concentrated on the broad aspects of the subject.

We may begin with the Greater Appalachian chain. This chain is commonly described as beginning in Alabama, continuing northeastward to New England, and on to Nova Scotia and the Gulf of St. Lawrence. But the chain does not stop at the Gulf or begin in Alabama.

In Alabama it plunges under a cover of sedimentary rocks laid down on the eroded Appalachian Mountains after these, for a length of hundreds of miles, had sunk below sea-level. Geologists have reason to think that the Appalachian structure continues beneath that sedimentary veneer, turns westward, and reappears well above sea-level in the mountains of Arkansas, Oklahoma, and Texas. Still farther west, the chain is cut across by the younger chain of the Rockies.

Returning to the east, we find the Appalachians represented in Newfoundland. On the eastern side of Newfoundland, just as at the eastern end of Nova Scotia, the visible part of the chain is cut off sharply by the Atlantic. The Appalachian structure continues out under the ocean. How far? This is a question for the next chapter. See page 284.

We cross to Cornwall and Brittany and find similar rocks and a similar folded structure. The folds were developed at the same epoch of the earth's history as that when the Appalachians were built. The same old chain continues into Belgium, Germany, southern Russia, and then all across Asia into China. It includes the famous Harz Mountains; hence some geologists have named this immense unit, traversing Eurasia, the *Hercynian* chain (Figure 169, page 281). An alternative designation is "The Altaide Chain," derived from the name of the Altai Mountains, in Asia.

Locally the rocks that were long ago folded into the Hercynian system of mountains have again been folded to form the younger Mediterranean Zone, already considered at some length. In general, however, the Hercynian chain lies a little north of, and parallel to, the younger chain. *Twice*, therefore, a mid-latitude, east-west belt of Eurasia has been heavily blanketed with sediments and then built into mountain ranges of the

first order. The Ural Mountain range represents a north-south branch of the Hercynian system.

The Greater Appalachian chain lies north of the younger Mediterranean chain of the West Indies and southern Mexico. In spite of its irregular ground-plan, the Greater Appalachian system may be regarded as an east-west zone of the earth.

Almost equally ancient east-west ranges are found also in the middle latitudes of the southern hemisphere (Figure 169). Their visible parts are typical ranges in Argentina, the Cape Province of South Africa, and probably Australia. The African range runs east and west, just north of the Cape of Good Hope. It is cut off at each end by the ocean, but it sends a branch to the north for some distance along the Atlantic coast.

Still older than the Appalachians or Hercynians, is a mountain belt, the wrecked fragments of which appear in north Scotland and along the western slope of the Scandinavian Peninsula. Probably the belt really continues into Spitzbergen and curves around to form the islands which are situated north and northwest of Greenland. This zone of deformation has been called the *Caledonian* system of mountain structure.

Except a few, relatively small chains, like the Ural and Caledonian chains, the mountains of the earth are now seen to be rather well organized into two grand classes.

The first class includes *East-West Mid-Latitude Zones* of chains in both the Old and New Worlds, and also in both the northern and southern hemispheres. The mid-latitude chains of the northern hemisphere comprise the younger Antillean and Alpine-Himalayan chain and the older Appalachian and Hercynian chains. There is no equivalent of the younger mid-latitude chain in the southern hemisphere; but there the ranges of Argentina, South Africa, and Australia match the Appalachian-Hercynian unit of the north.

The second principal group of chains is the relatively young *Circum-Pacific Zone* of mountains, emerged and submerged.

Nearly all the rest of the continental areas have not seen pronounced folding and thrusting, ever since a time that long

antedated even the oldest of the chains we have reviewed. For example, since that early time, the extensive terrane including northern Canada and Greenland, has been gently warped but not mountain-built. Like a strong plate, this broad expanse of the earth's crust has refused to yield and become folded. It is shaped roughly like a shield; hence it has been called the Canadian Shield. Like a buckler, it is stiff and strong. We note its position on the map (Figure 153), where this and other shields are indicated by stippling.

Across the Atlantic is the similar Russo-Scandinavian Shield, extending from Sweden to the Urals, and from the Arctic nearly to the Caucasus. Beyond the Urals is the still vaster Siberian Shield.

South of the northern, mid-latitude, mediterranean zone of mountain chains, are extensive, likewise stable areas of the earth's crust. They include the Brazilian Shield, the Antarctic Shield, the Australian Shield, the Indian Shield, and the African Shield, the greatest of all (Figure 153).

In general, we may say that the more stable parts of the continental crust are situated in the *high latitudes* of both the northern and southern hemispheres; and in a *broad equatorial belt*, including Brazil, most of Africa, and Peninsular India. The last chapter contained the statement that these same areas have tended to stand above sea-level. Hence they have been the chief areas of prolonged erosion. Detritus washed from their surfaces has constituted the major geosynclinal prisms, whether in mid-latitudes or along the border of the Pacific. From the stable parts of the continents, the raw material of the mountains was obtained. Between the stiffer, more unyielding, higher parts of the earth's crust, the sedimentary prisms were then squeezed, crumpled, and rafted together. There the world mountain chains were chiefly built.

Much older than any of the ranged mountains of the globe —those so far described—and incomparably more extensive than all of them together, is the complex structure of the *shields themselves*. Wherever exposed, the shield rocks of Canada, Scandi-

FIG. 153. WORLD-MAP, SHOWING THE POSITIONS OF THE SHIELDS AND OF THE TWO MAJOR ZONES OF DOWN-WARPING; ON MERCATOR'S PROJECTION, WHICH GREATLY EXAGGERATES AREAS IN HIGH LATITUDES.

navia, Finland, Siberia, India, Australia, Africa, Antarctica, and Brazil show evidence of having been deformed. The folding, upturning, thrusting, and mashing of these most ancient rocks

FIG. 154. THE INNER GORGE OF THE COLORADO CANYON, ARIZONA, SHOWING THE BASEMENT COMPLEX OF ROCKS BENEATH A MUCH YOUNGER COVER OF FLAT STRATA.

are manifest to a degree seldom equaled, over large areas, in any of the familiar mountain chains.

Not only so. The same complexity of structure is found in the basement rocks on which the geosynclinal and all other, thinner, sediments were deposited. Here and there the basement can be seen beneath the sediments. A well-known example is at the Grand Canyon of the Colorado River. In the photograph (Figure 154) may be seen the inner canyon, cut in the old Basement Complex. Above it lie the layered rocks, much younger, which lend the renowned architectural quality to the canyon scenery.

Far away, in northeastern Labrador, we have the same thing in principle. The 1,500-foot cliff, shown in Figure 155, has been cut in a bedded series of sedimentary rocks resting on the shield complex, here, as usual, granitic in nature and therefore much lighter in color than the overlying mudstones and other strata.

Photograph by the author.

FIG. 155. THE 1500-FOOT CLIFF AT CAPE MUGFORD, LABRADOR, SHOWING THE LIGHT TINTED ROCKS OF THE BASEMENT COMPLEX UNDERLYING MUCH YOUNGER STRATA WHICH ARE LITTLE DEFORMED.

At intervals all over North America the Basement Complex has been warped up, and any mantle of younger sediments that may have once covered it has been eroded off, exposing the complex. In Figure 156 we note the main part of the Canadian Shield as exposed to the air; it is marked by the dotted pattern. The smaller exposures of the same complex are shown in solid black. But all of these exposures of the complex are connected underground, beneath the superficial pellicle of ordinary stratified rocks, such as those of the plains of the Middle West.

Similar relations are found in all the other continents. In

fact, below their generally thin mantles of sedimentary rock, all of the continents are made up of this structurally complicated mass of rocks. The chief constituent is granite, which by heat and

FIG. 156. MAP SHOWING THE OUTCROPS OF PRE-CAMBRIAN ROCKS IN NORTH AMERICA. (After Miller in "Historical Geology," D. Van Nostrand Company, New York.)

pressure has been largely converted into a layered crystalline rock, called gneiss (Figure 54, page 97). Like many other layered rocks of the complex, the gneiss is often seen to be crumpled to a bewildering degree.

Evidently we have in the Basement Complex of the continents an enormous mountain structure of a kind. So old is it that most of the original rough relief has been wiped out by erosion. The true nature of the complex is, therefore, not expressed in the topography; it can only be determined by patient expert study of outcrop after outcrop of rock over millions, yes, tens of millions, of square miles. All other visible formations of the globe are dwarfed beside it.

The oldest of our mountain structures is, then, as extensive as the continents themselves, and it is by long odds the most complicated known to the student of mountains.

Because of its size and intricacy of structure, the Basement Complex has been geologically mapped only in a few, relatively limited regions. So far as exploration has gone, it seems that the rock folds of the complex are not nearly so systematically aligned in definite chains as the folds and thrusts of the younger mountains. The ancient deformation seems not to have been particularly dependent upon a preliminary weakening of the crust by deep sedimentation. Apparently the earth's crust was then thin, thin because the earth was hotter than now. The crust was therefore weak. Strong forces acted on this weak crust, giving effects of distortion beyond compare.

Summary

We have reviewed the two master systems of high and rugged, because relatively young, mountains.

The east-west Mediterranean Belt of young, high mountains is confined to the northern hemisphere. It is represented throughout the full length of Eurasia, as well as in the West Indies and Central America. Clearly, the forces responsible for the building of this long zone of mountains acted along general north-and-south lines.

The second master system is the Circum-Pacific Belt, more than twice as long as the Mediterranean Belt. The enormous mountain girdle of the Pacific was clearly due to forces directed from the continents toward the Pacific basin.

Both belts of mountains originated at corresponding zones of the earth, where sediment had long accumulated within sinking geosynclines or basins.

We have seen that the essential element in the formation of the mountain chains has been the horizontal compression of the earth's crust along the geosynclinal belts. Illustrations of the folding and thrusting together of the strata, caused by such compression, have been given. We saw, too, that the compressive force has been powerful enough to push the crumpled masses of sediments scores of miles over the rest of the earth's solid body. The result is asymmetry for the ground-plans or maps of many ranges. These are arranged in arcs. Some of the arcs have the garland or festoon form.

Thus, so far, the structure of great mountain chains has been explained by geologists. What about the great height of mountains? It is found that deformation of the rocks has not been directly, immediately, accompanied by strong uplift. On the contrary, the great heights of existing mountains are the result of broad upheaval of the belts, already folded. Each upheaval has taken place long after the respective mountain structures, such as arches and troughs, had been finally completed. This new question will be considered in the next chapter.

Then we reviewed the older mountain chains of the first rank, the Appalachian and its equivalent in the Old World, the Hercynian chain; both of these in the northern hemisphere. The corresponding east-west, mid-latitude, old chains of the southern hemisphere appear in South America, in South Africa, and probably in Australia.

Oldest of all is that immense mountain-built structure which has been called the Basement Complex. It is practically as extensive as the continents themselves. It largely composes the continental plateaus, and that to the depth of many miles. It underlies the geosynclinal prisms of younger sediments, out of which the more familiar mountain ranges have been made.

Large parts of this very ancient complex have long been free from strong folding or crushing. These parts, called "shields,"

were stiffened ages ago and remain specially unyielding regions of the earth's crust. From remote times they have tended to persist as land surfaces. Those lands, while being eroded, have furnished the detritus which formed the geosynclinal prisms, and later therefore the substance of the younger mountain ranges.

The shields were clustered around the north and south poles of the earth, and also along the equator. The down-warped geosynclinal belts have been developed with east-west trend, and in the middle latitudes of the northern and southern hemispheres; and also along the borders of the Pacific basin.

The next chapter will be concerned with the origin of the mountain chains, with the more remote cause of mountain-building.

CHAPTER VII

ORIGIN OF MOUNTAIN RANGES

THE essence of a mountain mass is not form or height, but structure; its component rocks have been deformed, thrown out of their original levels, by tilting or folding. Initially the strata lay flat (Figure 137, page 220). Figure 157 shows how deformed sedimentary rocks have been cut across by the powerfully erosive waves of the Scottish coast. The waves care not what may be the attitude of the rocks, whether horizontal, simply tilted, or folded, and delight in sawing through strata with any attitude. In this photograph we see a syncline or trough-shaped mass of strata pitching seaward and cleanly truncated. If the picture had been taken at high tide we should have looked upon the curling waves of the sea; we could not have suspected that a bit of a mountain range lay beneath.

How and why have strata been so deformed, deleveled? Three subordinate modes will be briefly noted before discussing the fourth and principal mode, that by horizontal compression of the earth's crust.

1. At each of many localities molten rock, or magma, has risen along cracks through the lower part of the crust and reached a plane of bedding in a set of stratified rocks. Along that plane the magma has spread out, forcing up and doming the overlying strata. Such an intrusive body of lava we have learned to call a laccolith. Figures 97 and 98 (page 162) illustrate this cause for the upturning of strata and a kind of mountain structure. Such laccolithic mountains are always of relatively small extent. Classic examples are found in the Henry Mountains of Utah, and the Highwood and Judith Mountains of Montana.

2. More rarely the earth's crust, including its sedimentary veneer, has been strongly basined by the large-scale eruption of

the substratum glass or magma to the surface. This transfer of material removes support for the crust which overlies the source of the magma, or lava. The lava weighs heavily on the surface of the earth's crust. For the double reason the crust beneath the great flood of lava sinks. The crust with its cover of strati-

Photograph from the Scottish Geological Survey.

FIG. 157. PLAIN OF MARINE EROSION ON FOLDED CARBONIFEROUS STRATA, NEAR WEAKLAW, HADDINGTONSHIRE.

fied rocks becomes basined. The strata become notably tilted; we have a mountain structure of a second, special kind.

Probably the grandest of all examples is to be found in the Bushveld of the Transvaal, South Africa. There, lava from the substratum was poured out on the surface, as well as intruded between the older stratified rocks near the surface. Tens of thousands of cubic miles of molten rock were thus locally transferred from beneath the crust nearly or quite to its surface.

The transfer of material caused so pronounced a basining of the crust that its strata were tilted inward on all sides of the eruptive mass, at angles of 5 to 10 degrees from their original,

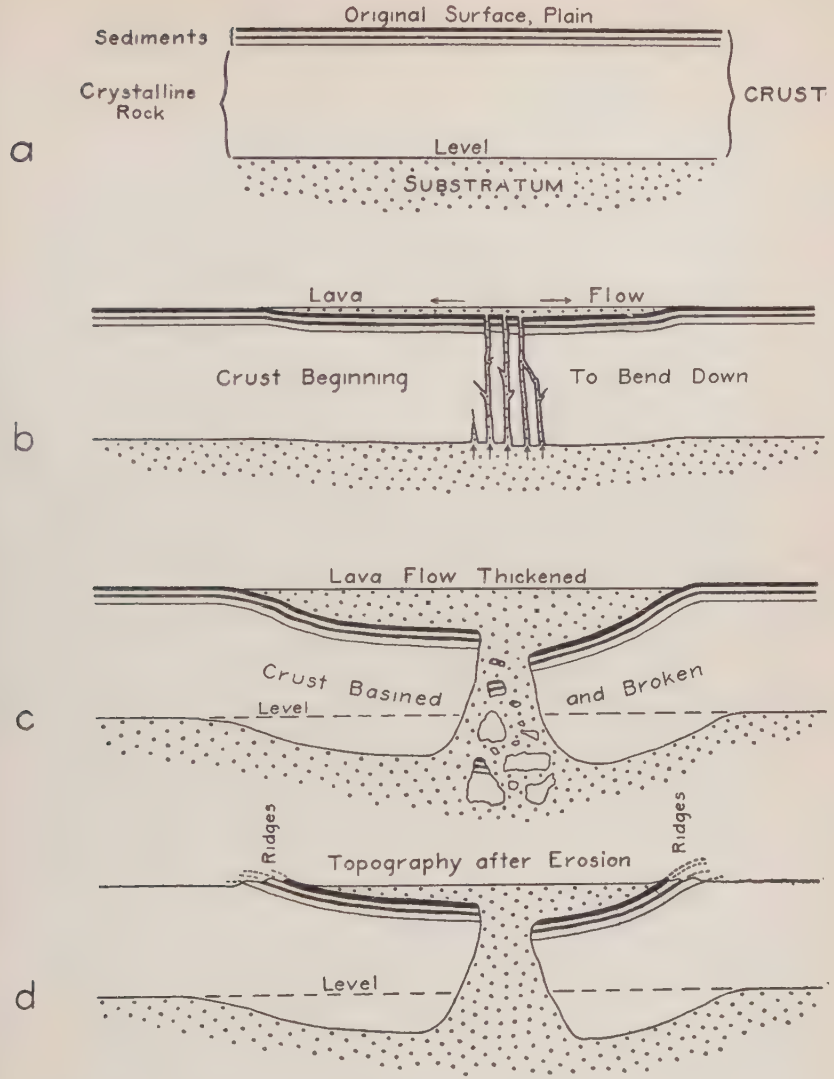


FIG. 158. FLEXURE OF THE CRUST AND MOUNTAIN-MAKING IN THE TRANSVAAL.

The sediments are nearly four miles in thickness.

almost perfectly horizontal position. For reasons that are not yet well understood these centripetal dips of the strata were later increased to angles locally reaching as much as 20 to 50 degrees. Figure 158 is a series of sections representing the

sequence of events. Each section is merely a diagram and is not drawn quite to natural scale. The scale is the same for all four sections. It may be gauged by the fact that the distance between the innermost ridges of mountains in Section *d* is of the order of 100 miles. Similar cross-sections, which might be made at right angles to those actually drawn, would be nearly three times as long. The total length of the mountainous rim of the Bushveld basin is 600 miles or more.

Section *a* shows the original position of the thick cover of sedimentary rocks resting on the much older crust rocks, which here, as in most of Africa, are granites. See Figure 51, page 93.

The crust was cracked through, and basaltic magma from the substratum (dotted) rose along the cracks. Reaching the thick veneer of sedimentary rocks, the molten magma was thrust into the strata horizontally, forming many large sills or intrusive sheets. These sheets spread laterally from the feeding cracks until they attained areas of thousands of square miles. The sheets of molten rock then froze or crystallized and became parts of the upper part of the earth's crust. The magma also broke through to the surface and was poured out as a colossal lava flow. The transfer of so much magma from below the crust to the surface, or nearly to the surface, naturally caused the crust to bend down. The initial stage of this down-bending is illustrated in Section *b*, where for simplicity the intrusive sheets are not shown, the whole composite mass of igneous rock being represented as a "lava flow."

Section *c* indicates a later stage of the process. Much more magma has risen from the depths, and the crust has bent down correspondingly. The down-bending led to tensions in the central region, so that the crust became broken into blocks. Those blocks varied in density. Some of them were denser than the substratum magma and sank into the depths, where they were more or less completely melted or dissolved. Thus new, secondary magma was generated, and this too rose to, or toward, the earth's surface.

The eruptions ceased. The lavas and the intruded magmas

froze solid. Then began a prolonged period of erosion, during which thousands of feet of sedimentary and igneous rock were removed from every part of the Bushveld. The erosion has gone so far that the sedimentary rocks have been swept away all around the "lava flow," except where the strata slope or dip strongly under the "flow." The strata differ in their resistance

Photograph by the author.

FIG. 159. RIDGE OF QUARTZITIC SANDSTONE, BUSHVELD, NEAR PRETORIA; SOUTH SIDE OF THE ERUPTIVE COMPLEX.

The sandstone dips north, under the eruptive rock, which is behind the ridge.

to the erosive agents; hence some of them project as ridges, while the softer strata underlie the valleys between those ridges. Section *d* shows the present condition of the Bushveld basin. Comparison with Section *c* shows how great has been the erosion through the long ages since the basining took place.

Sections, similar in principle, could be made in any direction through the center of the basin, which is 300 miles long and more than 100 miles wide—an area comparable to the French and Swiss Alps together.

The sections attain more meaning if we look at some photographs of the mountain ridges which have been eroded out of the tilted beds of sedimentary rock; that is, the strata surround-

ing the eruptive mass and dipping under it. However, it should be remembered that no pictures can adequately portray these impressive ridges. In the clear air of the Transvaal they can be seen sweeping along in their grand curves through a distance of 50 miles at a time.

Figure 159 is a view near Pretoria, looking northward. The hard sandstones of the notched ridge in the background are dipping or sloping northward, under the enormous igneous "flow," which lies behind the ridge. Back of the camera was a similar ridge, parallel to that in the view. Between the two ridges is an equally long, flat-floored valley, the plain of the foreground. This valley is located on the upturned edge of a thick band of soft shales. The two ridges and the valley together represent only part of the width of the mountain structure.

Figure 160 shows another great layer of hard sandstones, dipping under the eruptive mass at the eastern end of the Bushveld basin.

Figure 161 is a photograph of still another set of the strong beds of sandstone, dipping under the eruptive mass, but here on the north side of the basin. The angle of dip is about 45 degrees, and nearly the maximum observed in the 600-mile periphery of this remarkable structure.

3. A much commoner mode of mountain-building is by the slipping of blocks of the earth's crust, under their own weight, along steeply inclined fractures. Movement of this kind we have learned to call faulting. Here the underpinning of the blocks was insecure, but the insecurity and consequent dislocations were not demonstrably due to the transfer of magma within the earth. Faulting is common in mountain chains which had already been built by horizontal compression of its rocks. After the paroxysm of folding and thrusting, the earth's crust is not in a state of ease. Readjustments take place, and one effect is the breaking of the crumpled mass into blocks, which settle into new positions. Usually each block is rotated somewhat as it settles down. In a section of the Connecticut Valley region during a former geological period (Figure 178, page 296) we see

Photograph by the author.

FIG. 160. RIDGE OF QUARTZITIC SANDSTONE, BUSHVELD; EAST SIDE OF THE ERUPTIVE COMPLEX.

The sandstone dips west, under the eruptive rock, which is behind the ridge.

Photograph by F. E. Wright.

FIG. 161. RIDGES OF QUARTZITIC SANDSTONE, NEAR MALIPSDRIFT, BUSHVELD; NORTH SIDE OF THE ERUPTIVE COMPLEX.

The sandstones dip south, under the eruptive rock, which lies to the right of the area photographed.

how the sandstone beds and the older, underlying, greatly deformed rocks of the old Appalachian Mountains have been broken into fault-blocks. Mountains of this kind, in Utah, are so young that they now stand high in spite of erosion. The mountain in the background of the picture, Figure 52, page 94, is an example. The railway-train has to struggle to get up the grade

FIG. 162. THE SIERRA NEVADA SEEN FROM MONO LAKE, ILLUSTRATING A GREATLY ERODED FAULT-BLOCK.

on the eastern slope of the Sierra Nevada. That slope is the greatly eroded face of one of the largest fault-block masses of our Cordillera. Figure 162 is a photograph of the high Sierra Nevada block, looking westward across Mono Lake. The rock surface, on which the lake rests, used to stand more than a mile higher with respect to the Sierra block in the background; so pronounced was the faulting. Hundreds of other fault scarps are known in our western mountains.

4. Having listed the minor kinds of mountain structures, we are now to consider the fourth and most important kind. Here the main problem is the origin of the force responsible for the principal mountain chains. The preceding chapter gave the first part of the answer to this question, an answer agreed upon by

practically all geologists. It was there stated that folding, thrusting, and up-ending of strata are the necessary results of pressure, exerted at the ends of the originally flat beds; that is, horizontal pressure. We recall Figures 142 and 143, giving sections which illustrate the experimental imitation of mountain folds and thrusts by lateral pressure; and we remember that mountain ranges are chiefly made of geosynclinal prisms, that is, very extensive and thick lenses of sedimentary, stratified rocks.

We now attack the second part of the question of origin, namely: Why has there been horizontal compression of the rocks at all? There has been much discussion of this, one of the chief questions of natural history. I shall not attempt to weigh the relative merits of the various older theories of mountain-building. These theories, all more or less unsatisfactory, are noted in readily accessible text-books of geology. Less widely published is a new, startling explanation, first announced by an American geologist, Frank B. Taylor, and independently worked out by Alfred Wegener, a German meteorologist. Many geologists have found their idea bizarre, shocking; yet an increasing number of specialists in the problem are already convinced that it must be seriously entertained as the true basis for a sound theory of mountain-building. The subject has been under discussion only a few years and is laden with difficulties, so that a full and objective treatment is still impossible. Nevertheless, every educated person can not fail to be interested in this revolutionary conception.

Taylor and Wegener believe that the mountain chains of the globe were formed by the horizontal crushing of geosynclinal prisms which lay in front of *slowly moving, migrating continents*. For example, according to this hypothesis, the formation of our Rocky Mountain system was due to the slipping of all North America in a westerly direction, away from Europe, and that for a distance of hundreds of miles (Figure 163). This migration of the vast continental block took place under the direction of a force so powerful that the strata of the Rocky Mountain geosyncline were crumpled and thrust into mountain turmoil.

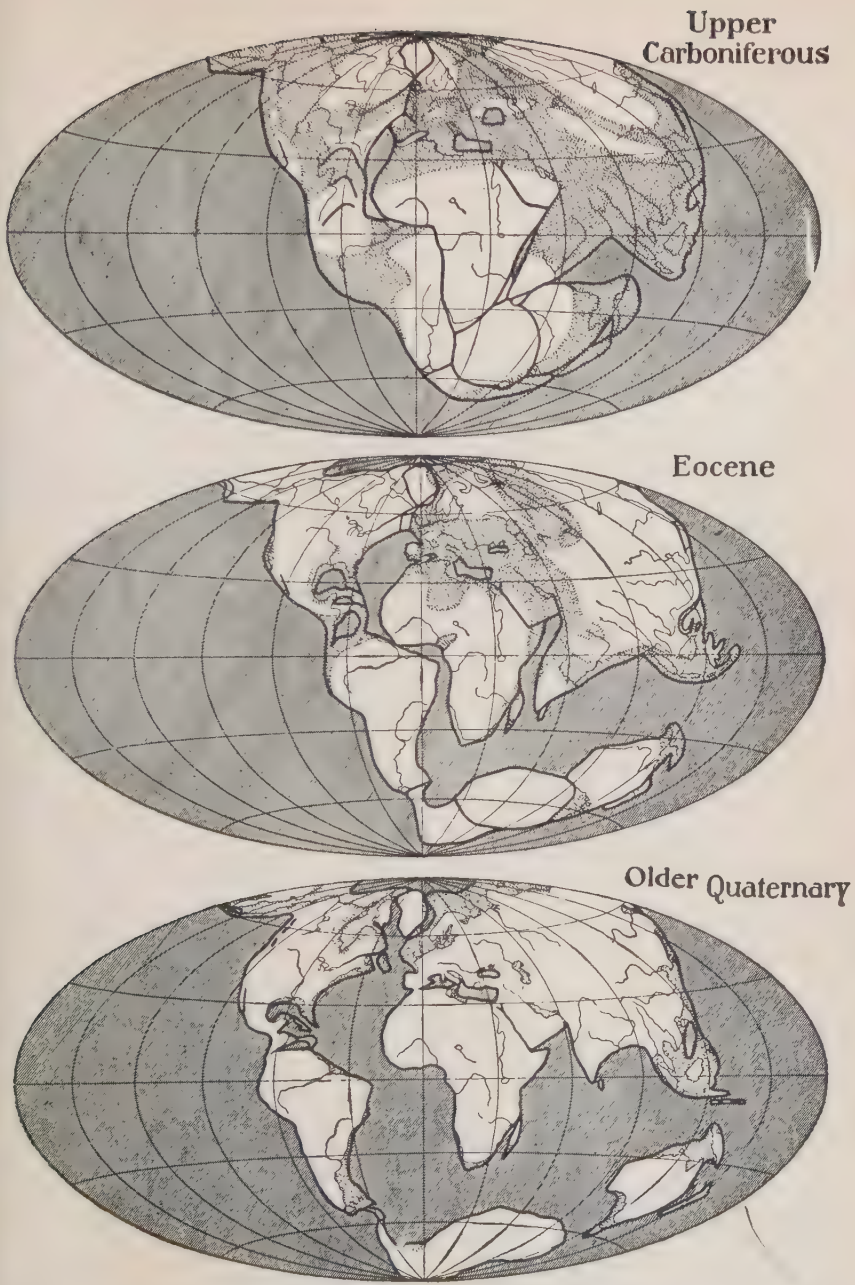


FIG. 163. WEGENER'S MAPS ILLUSTRATING HIS IDEA OF CONTINENTAL MIGRATION; THREE SUCCESSIVE STAGES REPRESENTED. (From His "Origin of Continents and Oceans," E. P. Dutton and Company, New York.)

Some geologists, especially European geologists, saw at once how the new hypothesis explains automatically not only mountains but also a dozen other mysteries in their science. But there is a difficulty. Neither Taylor nor Wegener has shown *why* the continents should move. They have not discovered the force which did the gigantic work of overcoming the resistances to continental migration. Nor have they evaluated those resistances. For these reasons geologists are going slow in placing such mobility of continents among the accepted principles of science.

This conservatism is justifiable until some one has discovered the force available for the movement of continents. To offer to the general reader a new suggestion on this fundamental question is a decidedly bold step. However, after prolonged study of the subject, I have come to the conclusion that the suggestion now to be presented is in principle unescapable, if the continents are not securely anchored and have bodily migrated. The supplementary hypothesis really implies a restatement of the idea of continental migration.

The general hypothesis is, then, to be presented in the following form: The continents appear to have slid down-hill, to have been pulled down, over the earth's body, by mere gravity; mountain structures appear to be the product of enormous, slow *landslides*. Each chain has been folded at the foot of a crust-block of continental dimensions which was not quite level, but slightly tilted. Because the continent was tilted, it pressed against a geosynclinal prism at the foot of the slope. The pressure was equal to a fraction of the whole weight of the huge continental block, with the thickness of the earth's crust, taken to be about 40 miles. In an analogous way, a ladder, inclined against a wall at a low angle, exerts at the foot of the ladder horizontal pressure, which is a fraction of the weight of the ladder.

A more detailed statement of the case may be made from two points of view. First, were the continents actually tilted toward the geosynclines before the respective mountain chains were formed? Secondly, why should the crust of the earth have been thus deleveled on this world scale?

First, then, as to the facts of ancient geographies. We have seen (Figure 153, page 243) that the Canadian-Greenland Shield stood up, high and dry, during most of geological time, while the United States was largely submerged. Similarly, the great Russo-Scandinavian and Siberian shields have tended to stand higher than the regions to the south. All three of these shields are high-latitude elements, clustered around the North Pole. They are relics of a great North Pole dome of high ground. They have stubbornly remained high ground throughout most of geological time. Similarly, Africa-Arabia and peninsular India have as stubbornly remained high ground. They are relics of a long crust-dome with axis near the equator. The Brazilian Shield is another relic of this equatorial belt of high ground. Just as mid-latitude United States was generally low and usually covered with transgressing seas, so a broad east-west, mid-latitude belt of Eurasia, from France to China, tended to be submerged under the sea.

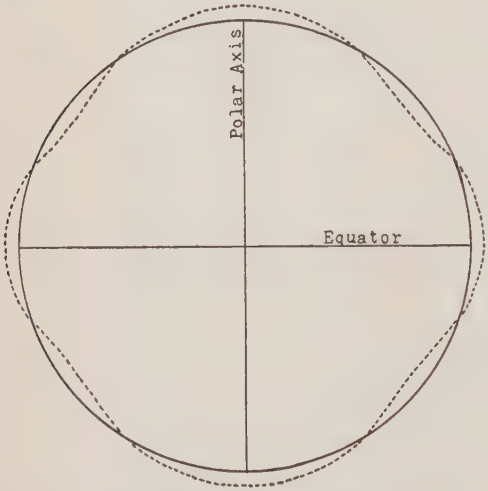


FIG. 164. SECTION THROUGH THE EARTH'S CENTER, ILLUSTRATING THE PRINCIPLE OF THE FURROWING OF THE SURFACE; THE INITIAL PROFILE GIVEN BY THE SOLID LINE.

Figure 153 shows where the mid-latitude seas transgressed in the northern and southern hemispheres. There were two mediterranean zones of down-warping. These mid-latitude zones were the sites of the principal east-west geosynclines and of the future Alpine-Himalayan, Antillean, Argentinian, and South African systems of mountains (Figure 169, page 281).

Before the mountain chains were formed, the globe tended to

assume a cross-section shown diagrammatically in Figure 164, which for clearness much exaggerates the effect.

Thus we have definite geological evidence that the earth's continental crust was rather systematically warped into polar domes and equatorial dome-arch, with two mid-latitude furrows north and south of the equator.

On the other hand, the crust of the land hemisphere, as *one whole*, clearly stood high above the level of the crust under the Pacific, or primitive, Ocean. There is good reason to believe, in fact, that the ancient land as a whole was slightly domed, so that this part of the earth's crust had on every side a general slope toward the Pacific.

Geosynclines were developed along the two mid-latitude furrows and also along the border of the Pacific Ocean.

Our second question, as to why the continental crust should have been gradually warped on this earth-scale, is much too involved for detailed discussion here. I shall attempt no more than an outline of what appears to be the best answer. For brevity the phrasing will be somewhat dogmatic. In this I beg the indulgence of the reader. It may be noted that Taylor had the general idea of continental sliding, but he gave no adequate explanation of the "hills" on which the continents have slid.

There are three principal reasons for such bodily distortion of the globe. *First*, the earth is distorted because it contracts. *Second*, the earth is distorted because its speed of rotation is changing. *Third*, the earth is distorted because its lands are being eroded. I shall specially discuss the first of these causes.

The first reason: the earth is distorted because it contracts. The earth is now constantly radiating heat from its interior, away into space. When the young earth was molten at the surface, the rate of radiation surpassed the present rate millions of times. The freezing of a surface shell or crust was rapid. A continuous crust was developed within only a few hundreds of years after the liquid stage had been established. See page 310.

The crust was, and is, a very poor conductor of heat. Hence, almost from the start, the surface temperature of the crusted

globe was controlled by the sun's heat. The infant earth had a surface temperature not essentially different from that now ruling. In short, the surface temperature has been very nearly constant all through geological time. That deduction is confirmed by the presence of fossils in strata which are very old, for the corresponding animals were fundamentally like living animals with respect to the small range of temperature which was tolerable and permitted the ancient animals to live at all.

Because, then, the crust was a poor conductor of heat, the upper part of it approached a condition of thermal isolation from the hot interior. Yet the isolation was not absolutely perfect. At this moment heat is slowly escaping across every square mile of the earth's crust. Throughout geological time the leakage of heat has continued. The earth's interior cools and, like the normal cooling substance, contracts.

The outermost part of the crust has practically constant temperature and, therefore, does not contract notably; the interior does. What must happen? The outer skin of the earth no longer fits the body beneath. The skin tends to fall in, so it will fit the rest of the body. The contraction leads to radial as well as horizontal tensions in the globe; the shrinking interior tends to pull in the crust. That tendency is resisted by the strength of the crust, with its dome shape. Because of its great area, the strength of the dome-shaped crust is very small. Of itself, a crustal dome of continental dimensions could not support much more than 1/1000 of its own weight. Even a small amount of internal shrinkage, with its downward pull on the crust, must suffice to initiate the infall of the crust.

The places where the crust must first fall in are determined by two principal factors. One is the weight of the ocean, which exerts a constant, very considerable pressure on its part of the earth's solid surface. Infall of the crust is also hastened by the downward pressure of the sediments which are constantly being washed down into geosynclines. The principle is the same in both cases. For brevity, we shall confine attention chiefly to the effect of the ocean's weight. The parallel effect of the weight

of a geosynclinal prism will be understood without formal statement.

The specially weighted crust under the ocean must, therefore, yield before the continental part of the crust yields. The suboceanic crust falls in as soon as the globe has contracted only very slightly. The adjacent continental part of the crust is at

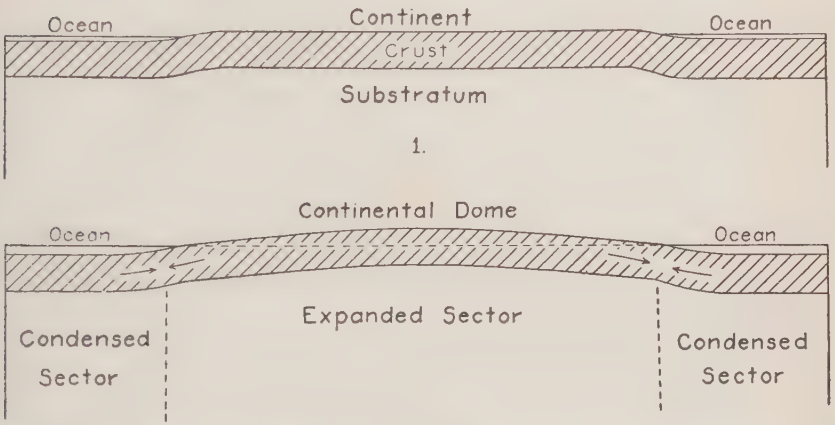


FIG. 165. SECTIONS ILLUSTRATING THE DEVELOPMENT OF STRESSES BY THE DOMING OF THE EARTH'S CRUST ON A CONTINENTAL SCALE.

once pressed from the sides by the sinking suboceanic crust, which has to accommodate itself to a slightly smaller area than it had before the collapse. Some lateral support is thus given to the continental part of the crust. This forms a residual dome standing above the sunken part of the earth's crust (Figure 165).

The continental dome has some, though small, strength. Because of that strength a little of the weight of the domed crust is removed from the underlying earth sector. In a similar way the whole of the weight of a cathedral dome is borne by wall and buttress; the air inside the artificial dome feels none of that pressure whatever. Through the relief of weight the earth sector, being somewhat compressible, expands elastically.

The material of the earth sector below the domed crust, having, through the elastic expansion, moved some distance away from the earth's center of gravity, has lost a little of its

own weight. This slight relief of pressure in the deep part of the sector causes matter to flow into that part from the adjacent compressed sectors. The domed sector thus comes to contain excess matter.

These changes tend to give the continental dome full support beneath. With further contraction of the globe the volume of the continental dome keeps growing. The height of the dome at its center does not grow in proportion, because the dome must ultimately be somewhat flattened by the flow of the weak substratum material outward from the center of the dome. Nevertheless, because the crust is strong, the domed sector continues to stand higher than its surroundings, and a dome shape persists.

Meantime the pressures in the crust at the foot of the dome are increasing. They are directed horizontally, or nearly so, as indicated by the arrows on the lower section of Figure 165.

Now at the foot of the dome is also the place where a geosyncline forms. In Chapter V we learned that the weakest part of the crust is located at a geosyncline, where sediments have been long accumulating.

When, therefore, the horizontal pressure reaches a certain intensity and the geosynclinal prism of sediments has reached sufficient thickness, the crust will break at the geosyncline. The dome is no longer firmly supported from the sides. Tensional pulls are generated at and near the center of the dome. There the crust becomes torn apart. The crust of the dome is torn into blocks or plates of the sizes of the existing continents. These blocks tend to slide slowly toward the geosynclinal.

To see the effect of the sliding, let us glance at Figure 166. The diagrammatic section above shows a geosynclinal prism by horizontal shading. The prism rests upon the older rocks of the crust, which here consists of a layer of "granitic" rock, overlying a layer of crystallized basalt. The crust is bent down into the hot, glassy basalt of the substratum, because of the weight of the geosynclinal prism. On the right, the crust is inclined, out of level. The arrow gives the direction in which this sloping part of the crust—the foot of the crustal dome just described—

tends to slide. That tendency means that pressure is directed horizontally against the right-hand side of the geosynclinal prism.

If the frictional and elastic resistance to down-sliding is not too great, the weak prism will be laterally compressed, folded,

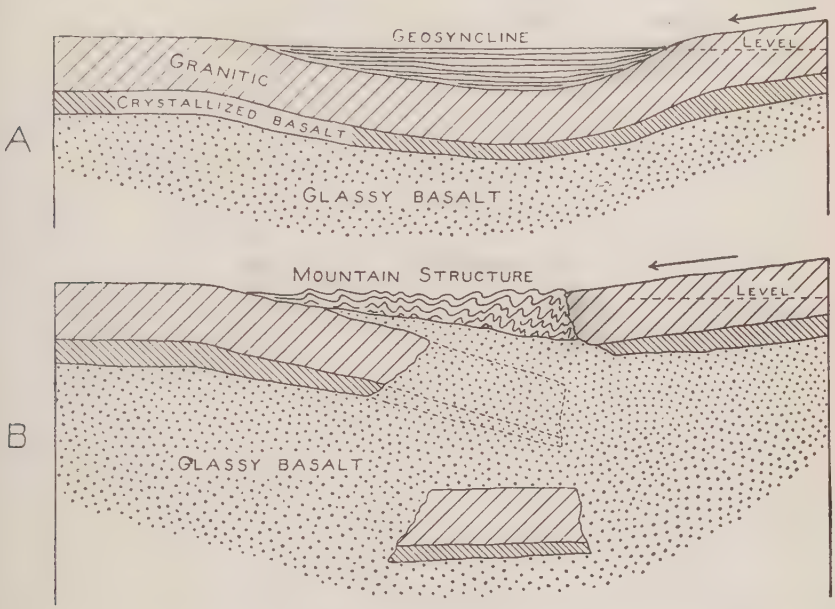


FIG. 166. DIAGRAMS ILLUSTRATING THE CRUMPLING OF GEOSYNCLINAL PRISMS OF LAYERED ROCKS BY THE SLIDING OF A LARGE BLOCK OF THE EARTH'S CRUST.

and rafted together; a new belt of mountain structure will be formed.

Here again, the physical nature of the substratum, the material just below the crust, is of crucial importance. Because it is hot glass it offers but very small resistance to slow sliding of the crust-fragment of the dome; in a sense, the *substratum is slippery.*

However, the sliding is resisted by the friction of the crystalline crust, a true solid, on crystalline crust.

Suppose, for example, that under the horizontally directed pressure, the crust breaks at the geosyncline. The sliding continental block, coming from the right (Figure 166), would tend

to press down the crust ahead of it. So far as it could succeed in that, the moving block would move and therewith tend to compress the geosynclinal prism somewhat. But analysis shows that the continental block would soon come to a halt because of friction, if the down-pressed part of the crust did not get out of the way. In this case strong folding of the rocks would be impossible.

But we found (page 110) that, because the substratum is glassy, it is slightly less dense than the crust above it. When, then, the crust cracks through and is locally forced down because of the pressure of the continental block, shown in Figure 166 as sloping toward the left, the immersed part of the crust breaks off and sinks some distance into the glassy substratum. Accordingly, the lower section shows a large piece of the foundered crust so immersed in the substratum, after breaking off from the position designated by the broken lines above. Note that the heavy crust under the left-hand part of the geosynclinal prism is bent down. This down-bending is also due to the difference of density between crust and substratum. The heavy part of the crust tears away from the light rocks of the geosynclinal prism and opens an inclined, widely gaping fissure, which is immediately filled with basaltic glass, the potential liquid of the substratum. Thus the sliding of the continental block is facilitated by the replacement of solid, crystalline rock of the crust by hot, plastic glass.

Meantime the geosynclinal strata have come to feel most of the full lateral pressure of the sliding continent. Being so light, the geosynclinal rocks can not founder. They remain at the earth's surface. But on these bedded, weak rocks there is an indefinitely great local concentration of the horizontal pressure exerted by the giant landslide. As time goes on, the maximum pressure shifts from place to place along the geosyncline. Under these circumstances, the lateral pinching of the geosynclinal prism suffices to cause folding and mountain structure. In the Section *B* we observe that the breadth of the belt of geosynclinal rocks has been diminished, as those strata have been crumpled into mountains.

The two diagrams were made on the assumption that the geosyncline had been formed on a continental plateau. If the down-warp were located on the original suboceanic crust, the mechanism of mountain-building would work in the same way.

This speculative explanation of mountain chains may, for convenience, be called the *down-sliding, or landslide, hypothesis.* As so far described, it depends upon the postulate of the earth's contraction. The first important effect of contraction is to warp the earth's crust out of level. In that state the crust has potential energy, *energy of position;* in other words, it can fall down and, when it falls, can *do work*—the work of mountain-building. This energy of position may be very much greater than the purely elastic energy which had been stored in the crust.

Before proceeding with the further analysis of the crust-sliding explanation of mountain chains, we shall do well to glance at some analogies.

The thin, glassy, plastic-solid crust which forms on the lava lake at Kilauea, Hawaii, is thrown out of level by the upward pressure of volcanic gas, which is constantly rising and expanding under certain parts of the lake surface (Figure 63, page 120). This deleveling of the glassy scum causes the scum or crust of the lake to break up into large fragments, like ice-floes. Each of these sheets of plastic-solid, flexible glass then proceeds to slide down the low slope. As it slides, it crumples its own substance on the down-stream side; hence the arches or folds in Figure 63. The folding is there due to the fact that the down-sliding crust of the lava encountered the rigid rocks forming the shore of the lava lake. The lava scum is analogous to the crust of the earth. The liquid lava below the scum is analogous to the glassy substratum under the earth's crust. The folds in the picture are analogous to mountain folds, such as we imagine to have been formed at the down-stream side of a sliding continent. However, the parallel is decidedly imperfect in one respect. The crumpling of the crust along the shore of the lava lake was also, and probably for the greater part, due to the viscous dragging of the crust against the shore rocks by convection currents in the liquid

lava beneath the crust or scum. Similar currents in the substratum are regarded, on the landslide hypothesis of mountain-building, as of little or no importance; mountain folds are primarily not "drag" folds but "push" folds. Compare the corded, arcuate folds of the lava-flow shown in Figure 55, page 98.

A clearer analogy is found in the sliding of the chilled upper

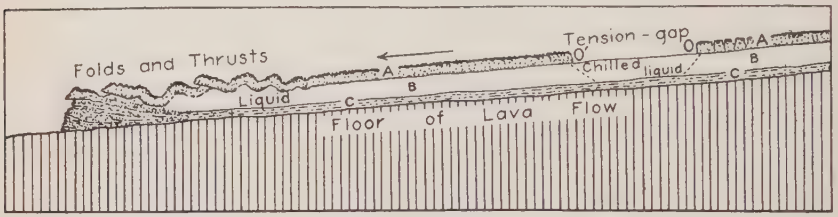


FIG. 167. SECTION OF A LAVA-FLOW. THE GLASSY SURFACE OF LAYER *B* WAS GROOVED AND STRIATED BY THE SLIDING OF LAYER *A*.

part of a basaltic lava-flow on the still hot and liquid interior of that flow, as illustrated by Figure 167. The diagram represents what I saw, some years ago, had taken place in the lava-flows of Ascension Island.

In the drawing the floor on which the flow ran is indicated by vertical lining. Against that floor the lava was chilled and a solid floor layer, *C*, was formed. The rapid radiation of heat into the air similarly caused the quick solidification of the surface layer, *A*. Between layers *A* and *C* the lava remained liquid, as layer *B*. Being on a slope, the heavy layer *A* slid on layer *B*.

Now, up-stream, layer *A* was held by friction on the sides of the flow, so that the part of *A* above the point *O* could not slide. The part of layer *A* below the point *O* tore away and slid through the distance *O*–*O'*. The glassy floor of the resulting gap is now grooved in the direction of sliding.

Down-stream, at the end of the flow, layer *A* was arrested in its sliding by the friction of solid on solid, for the solidification of a flow takes place at maximum speed at its lower end. The lava thus tended to make its own obstruction to further flow. Against the solid obstruction, layer *A* was pressed, as *A* slid

under its own weight. In consequence, folds and thrusts, exactly analogous to mountain folds and thrusts, were formed near the foot of the flow. So also layer *A* is analogous to our sliding continent; the liquid layer *B* is analogous to our hot, glassy, weak substratum below the mountain-building crust of the earth.

Perhaps with these analogies in mind, the reader is better able to tolerate the idea that the continents have slid over the hot glass of the substratum.

But cooling contraction is not the only cause for the deleveling or broad warping of the earth's crust. The other causes should be noted, if the down-sliding hypothesis is to be fairly presented.

The first of these causes is related to the fact that the rate of the earth's rotation is diminishing. At present the day is lengthening with extreme slowness—about one second in 100,000 years. However, there is good reason to assume a much more rapid lessening of the rate of spin during past geological time. Astronomers believe that the day was once many hours shorter than now. In early times the globe was much more bulged at the equator than it is now. As the rotation slowed down, the equatorial bulge tended to lessen and the polar axis to increase in length.

On account of mathematical difficulties, no one has yet been able to calculate what kind of shape the earth, with its solid crust, would assume because of diminished rotation. One thing, to be sure, is quite clear on analysis of the situation. As the earth slows down, its crust no longer fits the main body; it is too big to fit. Thus, for a second reason, we are bound to ask: How would the crust adapt itself to the new figure of the earth's body? The problem is closely allied to that of reshaping under contraction through cooling, where again the earth's skin is too big to fit the interior.

At present one can do little better than guess as to what shape the slowing-down earth would assume. My own guess is this: that the equatorial belt would continue to stand relatively high when compared with the mid-latitude belts, which would

also stand lower than the polar regions; in other words, that the original continental land would be furrowed in mid-latitudes, both in the northern and southern hemispheres. Figure 164 illustrates the point. It would profit the general reader little if I were to describe the reasons why such a guess has been formulated; the matter is too uncertain. On the other hand, the guessing has not been due to mere baseless curiosity about a mechanical puzzle. Rather it has been founded on hard fact. The furrows actually existed through much of geological time; traces of the furrows still exist in spite of obliteration during epochs of mountain-building. We will recall once more the earth's shape before Alps or Appalachians were formed.

The crust has strongly tended to remain above sea in very extensive continental regions surrounding the poles of the earth and in a similar region along the equator (Figure 153, page 243). These regions include the great shields of Canada, Russia-Scandinavia, Siberia, Africa, India, Brazil, and Antarctica. We remember that these were areas of nearly continuous erosion through most of geological time. We also remember the sites of the major east-west geosynclines, the major down-warps in the midst of the continents; they were two in number, one in each hemisphere, north and south. They were low belts, subject to transgression by the sea and to the deposition of sediments. They were our mid-latitude furrows in real life.

Looking back, our speculation has brought us thus far. Cooling contraction tended to dome the primitive continental lands, to warp down the suboceanic crust and, as well, the geosynclinal belts. Other forces, those set up by the diminution of the earth's rate of rotation, tended to make a double furrowing of the surface of the primitive land hemisphere (Figure 164, page 264). To understand the ancient geography of the globe, we must imagine a rather complexly warped surface.

Further, for reasons too technical to be here detailed, it appears probable that age-long erosion would perpetuate, and perhaps increase, the warping set up by the other two processes.

The three processes theoretically work together to delevel

the crust, according to the complex pattern of domes and furrows so rudely sketched. If all three processes were actually important, then there must have been a tendency for the continental crust to break up and slide in determined directions.

First, the primitive continent as a whole tended to break up, and its fragments to slide toward the primitive ocean basin. On the other hand, each relatively high polar dome tended to break up, its fragments to slide toward the equator. The elongated equatorial dome tended to break up, its fragments to slide to northward or southward. Evidently, the tendencies for sliding in the sense of the meridian were more or less balanced, so that all we could really look for would be indications that sliding took place toward one or both of the mid-latitude furrows; that is, toward the east-west geosynclines.

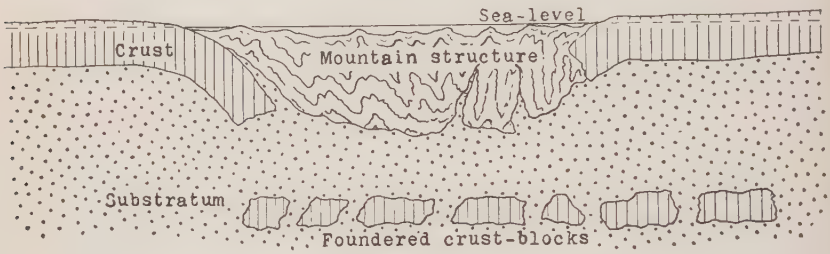
The validity of a scientific theory depends on its ability to account for observed facts. The sliding hypothesis can thus be tested in many ways. I shall briefly sketch nine different sets of facts, constituting as many different tests of the hypothesis. It seems to withstand all nine tests.

1. In a general way we see that the landslide explanation of mountains is pretty well matched by the actual distribution of mountain chains. The great east-west, mid-latitude, mediterranean zones of mountains and the still longer Circum-Pacific Zone are placed as our theory demands.

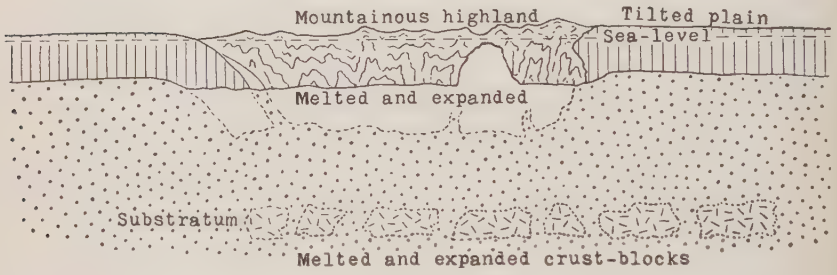
2. A second test is suggested immediately. After all, the landslide hypothesis has not yet been considered in relation to the forms of the actual mountains. Assuming that it can explain their structure, can it explain their great heights? It does not look reasonable that a sliding continental mass could push extensive masses of rocks up higher than itself; yet some of the younger chains of mountains are characteristically higher than the adjacent lands. In the last chapter we found, however, that all of the high ranges were much lower just after their folding; and that many young ranges are to-day submarine. Millions of years after folding, mountain ranges are upheaved bodily, in many cases thousands of feet. I think we can understand this if

we assume the earth to be what we pictured in the third chapter.

Each mountain structure was formed by the folding, thrusting-together, and rafting-together of strata. The mass of sedimentary and other rocks, which was thus developed with in-



1. Mountain belt is low just after folding



2. Later upheaval of mountain-belt because of thermal expansion of mountain roots and of foundered crust-blocks

FIG. 168. DIAGRAMS ILLUSTRATING THE CHIEF CAUSE OF MOUNTAIN HEIGHT.

creasing thickness, sank into the weak substratum. The deep roots of the mountains were at first cool. After millions of years the heat, slowly conducted up from the interior of the planet, could not fail to raise the temperature of the deeply sunken rock, and even to melt some of it. Heating and melting caused expansion, which meant that the crumpled mass above was as slowly, but effectively, uplifted. Following the upheaval, the many valleys have been cut by the rivers so invigorated, and between the valleys are the existing picturesque peaks and ridges. The

reasoning may be illustrated by two diagrammatic sections through the crust and the upper part of the substratum (Figure 168).

If a continental block has slid far, a wide area of the crust has been pressed down and overridden. This foundered rock sinks some distance into the substratum, as shown in Section No. 1, which also crudely portrays the mountain structure. At first, little or none of that structure is above sea-level. The foundered blocks come to rest at a given depth in the substratum, where the density matches that of the crust-blocks; for it will be remembered that the intrinsic density in this glassy layer of the earth slowly increases with depth.

Now look at Section No. 2. Glass and rock are poor conductors of heat; yet very slowly the foundered blocks become melted, that is, converted into glass, by the heat rising from the deep interior of the globe. Similarly, the deep roots of the mountain structure itself are heated and in part melted. The heating and the change of state, from crystalline-solid to glass, are accompanied by expansion. For example, the change of state involves an expansion to the extent of 6 to 10 per cent of the original volume. Hence the surface of the mountain-built crust is pushed up. The mountain structure has now become a mountain highland.

The melting of foundered blocks which are not directly under the mountain highland, namely, blocks which foundered as the geosynclinal prism was being crumpled and shoved from right to left (Figure 168), causes uplift of the region to the right of the mountains. Herein we would have explanation for the strong, comparatively recent uplift of the Great Plains of America and of the high plateaus of central Asia. Such broad upheaval, contemporaneous with that of the mountain system, is indicated at the place marked "Tilted plain" in Section No. 2.

3. Obviously the sliding of a continental block must be accompanied by tension on the upper edge of the block, the side opposite the mountain range. Vertical cracks open along that upper edge, cracks analogous to the tension-fissures or crevasses

in a glacier. Basaltic lava from the substratum rises into the cracks, and flows out over the surface. This appears to be one of the chief causes for the abyssal fissuring and injection described in the fourth chapter. Both dike and lava-flow quickly freeze. Renewed tension, cracking, and eruption of lava cause other dikes and flows; the dikes side by side, the flows superposed. Thus a new crust is formed along the upper edge of the moving continent. This crust, composed of crystallized basalt, is about 10 per cent denser than the dominant granitic rock of the continent. Hence the surface of the new crust will stand lower than the adjacent continental crust, so low as to be under the level of the primitive ocean. If the way is open, salt water runs in to cover the new crust. If the sliding continent has gone far, a new ocean basin is developed.

Is it too extreme to suggest that North America slid westward, crumpling rock beds into the structural turmoil of our Pacific Mountain System; that South America slid westward, folding the Andean strata on the way; that Eurasia slid eastward, crushing together the festooned arcs of eastern Asia; that the great rigid block of Australasia slid eastward, folding the rocks "down-stream" into the mountains of New Guinea, Fiji, and New Zealand? Was the sliding so prolonged as to open the new, wide basins of the Atlantic and Indian Oceans at the cost of the area of the primitive Pacific Ocean? Similarly, was the Arctic basin in part formed by southward sliding of both North America and Eurasia, when the east-west Mediterranean Zone of mountains of the northern hemisphere was created; in other part by the sliding of America and Eurasia toward the central Pacific?

Neither Taylor nor Wegener has described the evolution of the continents and oceans exactly along the lines of the foregoing questions, but both authors of the general hypothesis agree in believing continents to have migrated much more than 1,000 miles. Other geologists are more cautious and assume maximum migration of no more than a few tens or scores of miles. It is still too soon for any one to come to a definite conclusion on

the subject, but there seems to be no compelling evidence against the hypothesis that the Arctic, Atlantic, and Indian basins have been opened up by the horizontal movement of continents. Meantime, I shall continue to present the general conception in terms of the more generous estimate of the extent to which continents have moved.

4. The landslide explanation of mountains also accounts for the demonstrated former existence of broad lands east of North America and west of Europe; also broad lands east of South America and west of Africa; also broad lands between Africa and Australia. Before the new idea of continental migration was offered to science, it was thought by geologists that these lands had foundered, block by block, under the ocean. This older explanation of the Atlantic and Indian ocean-basins is fatally affected by difficulties arising from the physics of the case. We shall not enter on a discussion of those difficulties.

However, gigantic founderings of the kind are not necessary assumptions, if the two young ocean-basins have been opened by the migration of the continents. For, according to the migration theory, the missing land east of North America *was*, in large part, Europe and northern Africa. The missing land west of Europe and northern Africa *was*, in large part, North America; and so on.

This does not mean that small crust-blocks may not have sunk below sea. For example, there may be a basis of fact on which was founded Plato's account of the sinking land off the Pillars of Hercules, the Strait of Gibraltar: his legend of the Lost Atlantis, lost during Greek history. *Small* blocks of land might be expected to have sunk somewhat, during and after the crustal readjustments involved in continental migration.

The zone where the New and Old Worlds were torn apart is plausibly regarded as the so-called Mid-Atlantic Swell, which is a long and broad "ridge" on the ocean's floor; its height averages about one mile, or 1,600 meters. The map of Figure 169 bears contour lines of the Atlantic bottom, at 500-meter intervals, from the 4,000-meter contour upward. These lines locate

the Mid-Atlantic Swell. On its back the volcanic island of Ascension has been built. The ridge or swell is in the middle of the Atlantic basin, about half-way between Brazil and Africa. The Ascension Island and other volcanoes on the swell have erupted fragments of typical continental rocks to the surface. The swell may, therefore, conceivably represent a long strip of the original continent, a strip left behind when that continent was torn into fragments, which slid away, respectively to westward and to eastward. Other masses, like the rugged pile of the Azores, may also represent sunken pieces of the original continent. In any case, one would be wrong to assume that the whole width of the Atlantic is due to the horizontal movement of the existing continents. As already noted, the exact proportion of the basin which is to be so explained is a subject for future investigation.

Wegener has attempted to reconstruct the original continent. The uppermost drawing of Figure 163, page 261, illustrates his conception of what the lands were like in the so-called Carboniferous period of the earth's history. The Americas are shown cheek by jowl with the Old World. The middle map of the figure represents a stage when the sliding of the Americas had opened up the Atlantic Ocean, then narrow. The third map, below, represents a still later stage, when the migration of the continents had gone farther, the Atlantic basin being correspondingly widened.

Though in certain details the three maps can not be accurate, they serve to illuminate the general principle of the extensive horizontal displacements of land masses.

5. The new hypothesis automatically accounts for the general absence of mountain chains bordering the Atlantic, Arctic, and Indian Oceans. For in the more recent geological time these have been regions of tension, not of horizontal compression. On the other hand, the Pacific should be, and is, well framed in mountain chains. In brief, the Atlantic and Pacific types of coast-line, fundamental features of the earth, are adequately explained by the hypothesis of the migration of continents. Figure 169 is a map of the Atlantic basin with its great gulf-like exten-

FIG. 169. ATLANTIC TYPE OF COAST-LINE.

sion, the Arctic basin. The Circum-Pacific mountains of America are shown in solid black and are marked with the letter *P*. The east-west, older Hercynian-Appalachian system of the northern hemisphere is in part shown at *I* by axial lines. The slightly

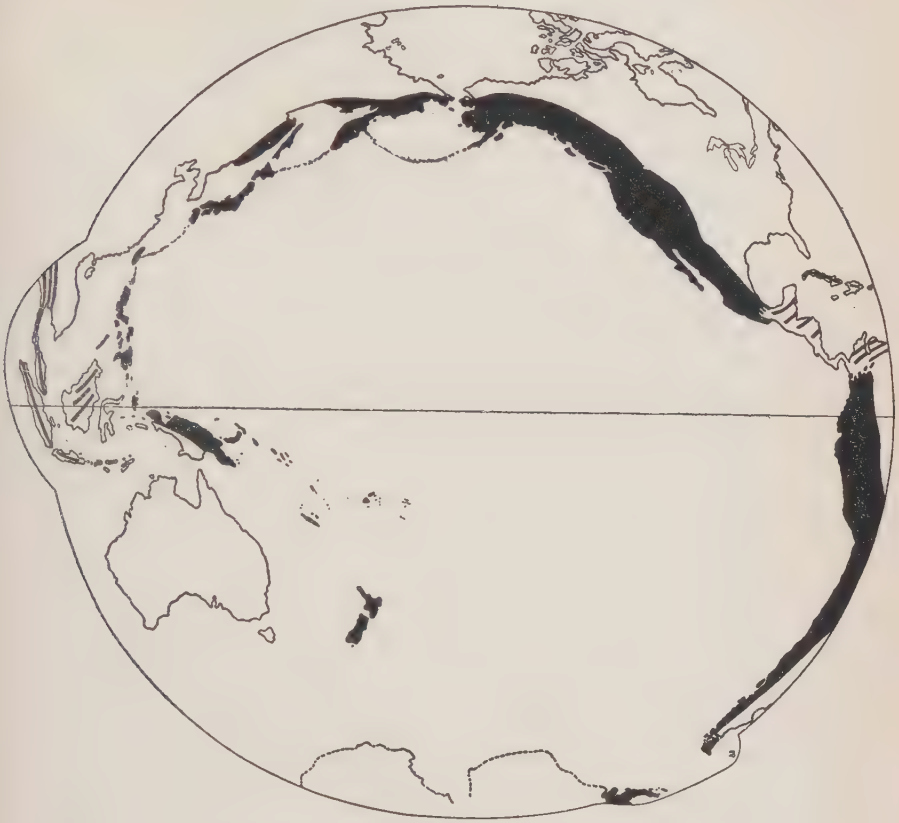


FIG. 170. PACIFIC TYPE OF COAST-LINE.
Scale about three-fourths that of Figure 169.

younger east-west system of the southern hemisphere outcrops in Argentina and South Africa at *II*, where again the axial trends or "directrices" are marked by short lines. The youngest east-west system, the Belt of Mediterranean Rugged Mountains, is similarly indicated at *III* in both the New and Old Worlds. The truncation of the mountain axes by the Atlantic coast is clear in every case. The contoured Mid-Atlantic Swell is a special

feature of the Atlantic basin; its possible significance has already been mentioned.

Figure 170 shows in solid black the outcrops of the Circum-Pacific Zone of mountains, above sea-level; it will be remembered that the bulk of this immense structure is hidden under the water of the ocean. In order to show the appearance of the young east-west zone of mountains (*III* of Figure 169) the solid black design representing the Circum-Pacific Zone is not applied over parts of the East and West Indies, though the rocks of both these regions were also mountain-built during the formation of the Cordilleras around the Pacific. The solid black of the map represents fairly well the axial trends of the Circum-Pacific Zone of chains, so that the general parallelism of those trends with the Pacific coast-line is portrayed. The Atlantic type of coast-line cross-cuts the grain of mountain chains; the Pacific type runs largely parallel with the grain.

6. If North America slid westward and Europe eastward, having been formerly joined together, then individual rock-structures of the original great mass of land were torn apart. The sundered parts of the structures should be visible in the existing continents. An absolutely exact matching of the structures seen along the respective coasts should not be expected. For on the Atlantic side of each continent, the edge of the rocky surface must have sunk down a little under the water. That the edges of the continents have actually been warped down is shown at our doors; the old-mountain surface of Massachusetts gently plunges under the Atlantic, and there makes up most of the 200-mile continental shelf off Boston. Further allowance has to be made for the drowning of small blocks, left behind, to sink some distance when the sliding took place. As just noted, such drowned lands may be represented in the Mid-Atlantic Swell.

Making all these allowances, one can hardly fail to be impressed with the remarkable matching of the rock structures on the two sides of the Atlantic. Thus, the Appalachians of Newfoundland and Nova Scotia correspond in composition, structure, and date of formation with the Hercynian mountain-mass

of Britain and Brittany (Figure 169). The old rocks of the Scottish Highlands are identical in habit and structure with the equally old rocks of Labrador. The famous Old Red Sandstone

FIG. 171. GLACIAL TILL OF CARBONIFEROUS AGE (DWYKA), SOUTH AFRICA.

of England has its mirror image in the Old Red Sandstone of Nova Scotia. The coal-beds of Britain and Belgium match well with the coal-beds of Pennsylvania.

Even more striking correspondence is found between the geology of South Africa and that of Argentina. A dozen peculiar

features of the one region are repeated in the other. Of the dozen I shall mention only one. In both of these mutually distant lands, thick deposits were made by glaciers, away back in the Paleozoic era, many tens of millions of years before the familiar *last* Glacial period began in North America. These ancient gla-

FIG. 172. GLACIALLY STRIATED PAVEMENT OF ROCK AT THE VAAL RIVER, NORTH OF KIMBERLEY, SOUTH AFRICA.

cial deposits of the southern hemisphere have been hardened into tough rock, a photograph of which is given in Figure 171. We note that it is an unstratified mass of rock fragments cemented by finer-grained material which is called boulder-clay. The technical name for this kind of deposit is "till," a Scottish word. Many New England hills, like Beacon Hill, Corey Hill, and most of the islands of Boston Harbor, are made of the relatively modern till, laid down by our own recent glacier that covered New England a few thousands of years ago. Similar material, though

so much older and now hardened into rock, has been found over an astonishingly large area in southern Africa.

At many places one can find the actual rocky floor on which these old glaciers of Africa crawled. That floor was beautifully striated and grooved by the boulder-shod glacier, exactly as the New England ledges have been striated by our more recent ice-cap. Figure 172 represents the floor on which the African ice-cap moved, near Kimberley; plainly seen is the smoothed, though grooved, character of this very old rock-ledge, a form which is never made by anything except a heavy, moving glacier, shod with fragments of rock. The ice here moved south.

Striated pavements of the same kind are found in South Australia, where a large glacier, contemporaneous with that of South Africa, molded the rocks.

Similar phenomena appear in Argentina, also on the large scale. Geologists who know them well are now doubting that the South African and South American deposits and markings were made by two separate ice-caps. Some of these geologists are sympathetic with the hypothesis of a forceful tearing apart of the two continents, and therewith the glaciated tract, since that old glaciation.

7. Let me recall still another test. The American geologist, F. B. Taylor, the man who first launched the hypothesis of extensive migration of the continents, got his inspiration from the curved, arc forms of the mountains of Asia. Before him, Eduard Suess, the noted Austrian geologist, had explained the Asiatic arcs by the bodily creep of Asia. After a life-time of study of the earth's plan, Suess concluded that the Himalaya was formed by the southward creep of northern Asia; the Japanese and neighboring mountain arcs, by creep of all Asia toward the Pacific. His idea has been greatly extended by Taylor, and, with modification, by Wegener. Figure 173 is a sketch-map, drawn by Taylor, to represent his conception of the manner in which the crust moved during the formation of the mountain arcs. (Compare Figure 152, page 235. The arcs are shown by the heavier black curves.) The continental crust is supposed by

Taylor to have moved away from the North Pole, crumpling the weak rocks of the geosynclines into mountain chains. The hypothesis now being presented is somewhat different, as it involves continental movement directly toward the central Pacific, as well as movement along the meridians; but the fact which is now of primary importance is that discerned by Taylor, who,

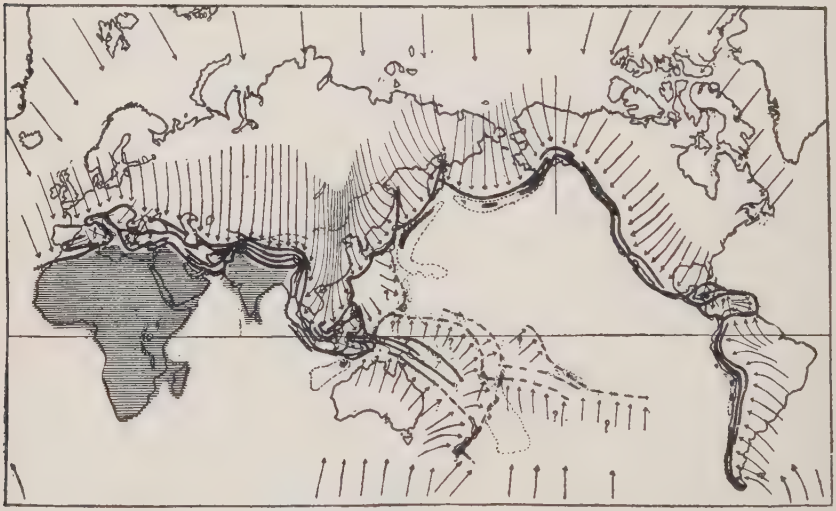


FIG. 173. TAYLOR'S WORLD-MAP, SHOWING HIS CONCEPTION OF THE MIGRATION OF CONTINENTS AND ASSOCIATED MOUNTAIN-BUILDING.

Mountain axes indicated by heavy lines.

sixteen years ago, emphasized the necessity of postulating crustal creep, bodily movements of continents, in order to explain the arcuate forms of the high mountain chains.

No other explanation of the remarkable garland shape of the Asiatic chains seems as good as this of Suess and Taylor. If we accept their explanation, then we can not avoid the assumption of a plastic movement of Asia at least as far as the average width of the arcs. I mean the width measured along the arrows that would fit each of the bows. The creep of Asia would thus be at least 200 miles. But if that continent could migrate 200 miles, there is no *a priori* reason for rejecting the hypothesis that

it has moved much farther. Similarly with the other continents that are fronted by mountain chains.

8. The landslide explanation of mountains demands that the crust shall have been pressed down in front of each sliding continent. On account of the strength of the crust, such trough-like depressions should long persist. A bathymetric map of the Pacific shows, in fact, a number of long deeps in front of the mountain arcs (Figures 3, 4, and 8). These great troughs are technically called foredeeps. Similar depressions are found in front of the intracontinental arcs. The foredeep facing the Himalayan arc has been filled with gravel, sand, and mud, washed thither by the mountain streams, and has been converted into a foreland (the "Geosyncline of Punjab" of Figure 152, page 235), but the original trough structure is patent to any geologist.

9. As already stated, the landslide hypothesis explains one of the long-standing mysteries of geology, the upheaval of mountainous belts and the surrounding regions long after folding has ceased. No other explanation of mountains accounts so well for this fundamental fact of geology.

But the supreme test of the landslide hypothesis is a complex matter of physics. Was the crust thrown out of level sufficiently? Why was it deleveled? What were the resistances offered to sliding of the crust? Would the horizontal pressure of a sliding continent suffice to fold beds of rock into mountains? To these very difficult problems speculative solutions have been offered. In brief, the conclusion of the argument is this: we may well ponder the idea that down-sliding of continental blocks and engulfment of other, smaller crust blocks down-stream have been the twin conditions for the building of mountains. The one condition depends on the warping, deleveling, of the earth's crust. The other condition depends on the difference of density between a crust block and the substratum into which that block has been pressed; the block must sink, out of the way.

The down-sliding of a continent can, of course, take place only if that movement is accompanied by return flow of mate-

rial below the crust. Space is lacking for a discussion of this phase of the subject. The probabilities are that the return flow would be distributed through a thick shell of the earth, perhaps more than 1,000 miles thick.

Summary

To sum up. The problem of this chapter is the manner in which the great mountain chains of the globe have been developed. The forces responsible for their folded structure were directed horizontally, and have been speculatively attributed to the down-sliding of continents. Before any of the epochs of mountain-building, the continental surface and the continental crust were not as level as now. They were warped, in the form of huge, gently sloping domes and basins. That is a fact, proved by geologists. Speculation enters when it is held that the crust in any one of these domes was sufficiently warped, thrown out of level, to compel its breaking up into fragments comparable with the existing continents, these crust fragments sliding down the flanks of the dome and crumpling the rocks ahead into mountain structures.

This new, landslide explanation of the principal mountain chains is offered for two reasons. First, none of the many older theories of mountain-building has proved satisfactory. Secondly, the new explanation seems to be supported by some special tests. Of these tests, nine have been briefly outlined. Among them, one may again be singled out for mention. After structure, the most characteristic feature of ordinary mountain chains is great height. At first sight, explanation of mountains by the falling of continental blocks does not seem to be reconcilable with the fact of high elevation of mountains above their surroundings. Yet, if the earth is constituted after the fashion described, every first-class chain must be bodily upheaved long after its folded structure has been developed. Assuming the landslide hypothesis to be correct, one can predict that broad, massive upheaval of the whole chain shall have taken place some millions of years after folding has ceased. Now geologists have recently come

to the conclusion that this expectation has been fulfilled in the case of every lofty range. Several others of the tests we have applied similarly involve prophecy of what ought to be observable in the make-up of the earth, if the landslide hypothesis is correct. In every instance, the hypothesis seems to stand this severest of all tests, the test of prophecy; that is, the agreement of observable consequences with the basal postulates of the hypothesis.

Thus, the explanation of mountain chains through the downsliding of continents appears to be able to answer our two initial questions: First, what is the cause of mountain structure? Secondly, what is the cause of mountain form? For, once upheaved, the mountain structure must be immediately attacked by the erosive agents, weather, rain, frost, and glaciers. These agents will see to it that the mountain structure shall be carved into such bold, impressive peaks and ridges as we find in the existing mountains.

Some emphasis has been placed on the difference of opinion, among those geologists who explain mountain-building by continental migration, as to the extent of the migration. Probably, in the light of facts now ascertained, we need not assume, for the formation of any one mountain chain, such continental displacement to the extent of more than a few scores of miles. Yet the problem of mountain-building does not stand alone. Closely connected with it is the likewise portentous problem of origin for the ocean basins. Already in this chapter the reader has perhaps found some satisfaction in the thought that all the ocean basins, except the Pacific, are products of truly extensive migrations of the existing continents. This topic will be necessarily resumed in the next and final chapter, which is the result of still more daring speculation concerning the development of the larger features of our globe. Throughout this whole discussion the reader will remember that speculation is not science or knowledge. Speculation, even that of the happiest kind, can do no more than point the way to possible future knowledge. Though it may stand on the right path, the sign-post is not the goal itself.

CHAPTER VIII

EVOLUTION OF THE FACE OF THE EARTH

According to Greek mythology, Proteus, the sea-god, had the power of assuming different shapes. Since the world began, the restless ocean has never repeated its shape exactly. The same is true of the solid earth. With great deliberation, yet none the less surely, the solid, crystalline crust of the earth has moved up and down, to and fro. It has been bent into broad swells and hollows; flexed into the sharp waves of the mountain structures; broken into large blocks and slabs, many of which have been rafted together; thickened by injections of lava, and by lava outwelling on the surface; thinned by melting, into glass, at the bottom.

The solid globe also is protean. Our present geography has been a gradual, epic development, the tracing of which is the privilege of the geologist—a privilege and a complicated task. The earth is a palimpsest. The record of its evolution has been written in rocks. Again and again the writing has been destroyed or obscured by erosion; or hidden underground by mountain-building or by sedimentation; or hidden under water by transgressions of the ocean upon the lands, where otherwise the geologist might travel and add to his facts. New writing has been done on the old. Let us look at two illustrations of the reading of the earth's history from the rocks.

The first illustration. Figure 174 is a view of a sea cliff in California. The lower half of the cliff shows a series of stratified rocks dipping into the ground, to the left. They form a minute fraction of an old mountain range. After that range was lifted above sea, it was long eroded by rain-wash, and finally its surface was cut across sharply by the ocean waves. The resulting very flat surface, which truncates the dipping beds of mountain

rocks, then sank farther below sea. Another series of sediments was deposited on the drowned surface. After that the region was uplifted. The Pacific waves once more attacked the buried range and also the thick cover of flat, younger, overlying sedi-

FIG. 174. SEA CLIFF NEAR MONTEREY, CALIFORNIA, SHOWING A MOUNTAIN STRUCTURE ERODED AND BURIED UNDER A THICK COVER OF ROCK.

ments. The latter we see in the upper part of the sea cliff, as rocks with horizontal bedding.

If it were not for the more recent uplift and for the cutting by the sea, there would be no exposure of the old mountain structure at this place. The geologist would see only the flat strata and might not even guess, merely from observations made just here, that mountain-building had ever occurred.

The second illustration is more elaborate. The late Joseph Barrell, of Yale, one of the profoundest of geologists, has vividly summarized the later history of the Connecticut Valley region. His diagrammatic cross-sections tell the tale (Figures 175 to 182).

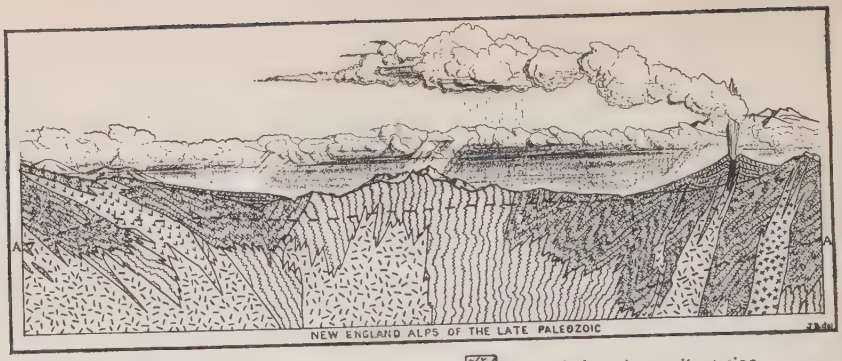

A
A
NEW ENGLAND ALPS OF THE LATE PALEOZOIC
Triassic sediments
Late Paleozoic lavas and tuffs
Paleozoic intrusive granite-gneiss
Paleozoic sediments
Pre-Paleozoic complex gneisses
0 Scale in miles, horizontal and vertical 10
A-A Depth reached by later cycles of erosion

FIG. 175. CONNECTICUT OF THE LATE PALEOZOIC TIME.

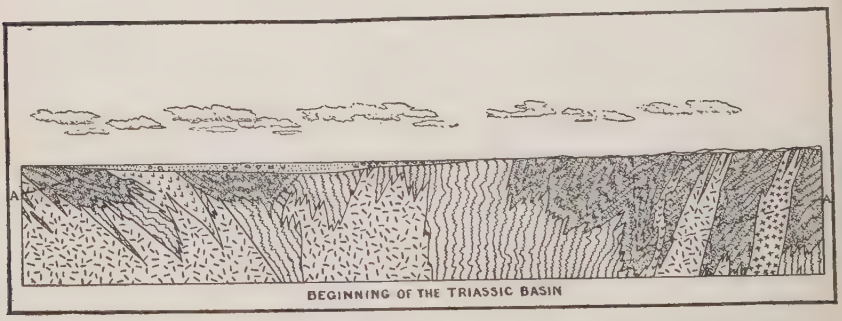


FIG. 176. CONNECTICUT AT THE BEGINNING OF TRIASSIC TIME.

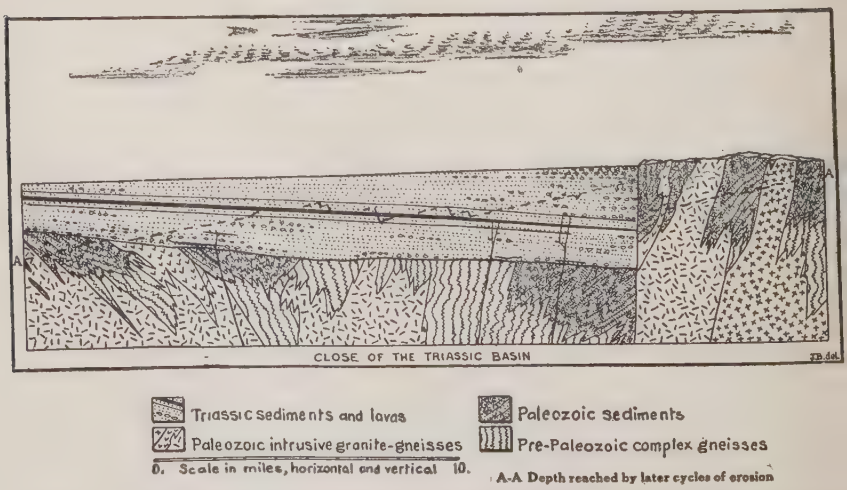


FIG. 177. CONNECTICUT WHEN THE TRIASSIC BASIN WAS COMPLETED.

Like all the rest of New England, Connecticut lies in the Greater Appalachian chain of mountains. These were formed during a truly revolutionary deformation of the earth's crust. The old stratified rocks, which during long ages had been accumulating in the Appalachian geosyncline, were folded, broken, and up-ended. The still older rocks of the Basement Complex, the universal foundation of all North America, were also caught in Nature's vise at the Connecticut Valley and again crumpled and mashed during the Appalachian revolution. Moreover, the roots of these Connecticut mountains were invaded by large masses of molten rock, magma, which soon froze and thus added solid granite and other igneous rocks to the Appalachian structure. Some of this underground lava bored its way to the surface, forming true volcanoes.

In the first cross-section (Figure 175), we see the folded, upturned sediments, shown by a lining pattern; the granitic intrusions, shown by a pattern of random short lines; and one of the smoking volcanoes at the surface. The cloud level suggests the considerable height of these young Appalachian mountains, even though already somewhat worn down by erosion.

Some millions of years passed. The mountains and volcanoes, well above sea-level, were slowly but surely eroded down by the ancient rivers, everywhere almost to sea-level. The rugged, mountainous relief produced by the Appalachian revolution was tamed down to a lowland, as indicated in the second cross-section (Figure 176).

Then something happened to the underpinning of the crust, which broke down along a master fault or fracture, indicated near the right-hand end of the section given in Figure 177. A large block of the worn-down mountain structure slowly sank along the nearly vertical fracture, the sinking being most pronounced at the right. Thereby a fault basin was developed. Into the basin, sands, gravels, and muds were washed from the surrounding lands. Under the weight of these new sediments their floor kept on sinking. Further deposition of sediments in the basin was compelled, until their total thickness reached many

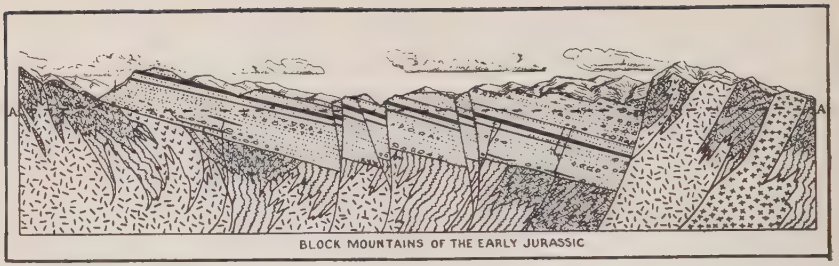


FIG. 178. BLOCK MOUNTAINS OF CONNECTICUT IN EARLY JURASSIC TIME.

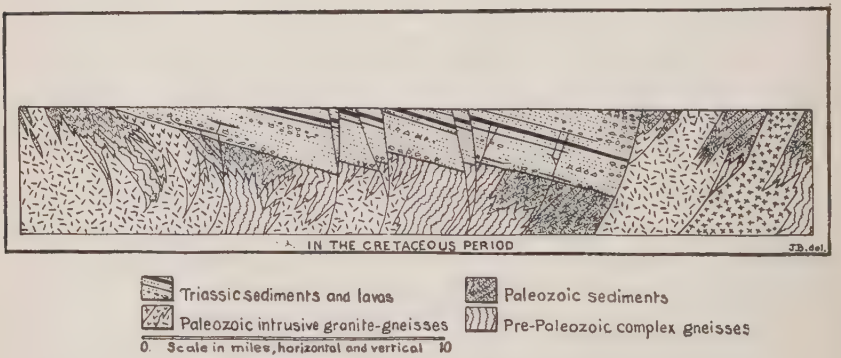


FIG. 179. CONNECTICUT IN THE CRETACEOUS PERIOD.

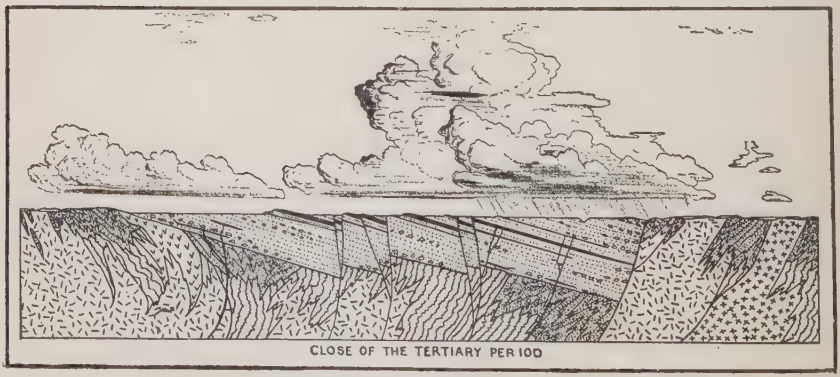


FIG. 180. CONNECTICUT AT THE CLOSE OF TERTIARY TIME.

thousands of feet. At intervals during the sedimentation basaltic lava rose from the substratum below the earth's crust and flooded the sandy plain.

In the cross-section, Figure 177, we see the buried old mountains, the thick sedimentary filling of the unsymmetrical basin (dotted), bounded on the right by the master fracture. We note also other fissures which represent channels, up which the basaltic lava rose. This lava formed three extensive flows, indicated by continuous black lines in the midst of the dotted sediments.

The long period of sedimentation came to an end, for there was renewed fracturing of the crust in this region. The old-mountain floor and the overlying sands, now hardened to form sandstone, were broken into fault-blocks. These blocks were tilted toward the right, as shown in the fourth cross-section (Figure 178). Thus a new kind of mountainous topography was developed, a fault-block topography. Its relief was notable, a fact suggested, here also, by the level of the cumulus clouds.

Once more there was prolonged quiet. The fault-block mountains were persistently attacked by the erosive agents and were reduced, like their Appalachian predecessors, to an almost plane surface, close to sea-level. The fifth cross-section (Figure 179) illustrates this step. We note the tilted, broken sandstones and the interbedded layers of solid lava.

Connecticut was then broadly lifted, well above sea-level. The rivers, which were steepened in their courses and therefore invigorated by the upheaval, cut out broad valleys on the relatively soft sandstone, leaving the harder, stronger beds of lava projecting as long ridges. This stage is indicated by the sixth cross-section (Figure 180). The master Connecticut Valley was etched out of the weak sandstone.

After the west-bound Boston and Albany trains leave the rougher eastern upland near Palmer, Mass., they run, via Springfield and Westfield, across a plain. The plain stands lower than the upland, because etched out by erosion on the up-turned beds of sandstone. The Mount Holyoke ridge to the north of the

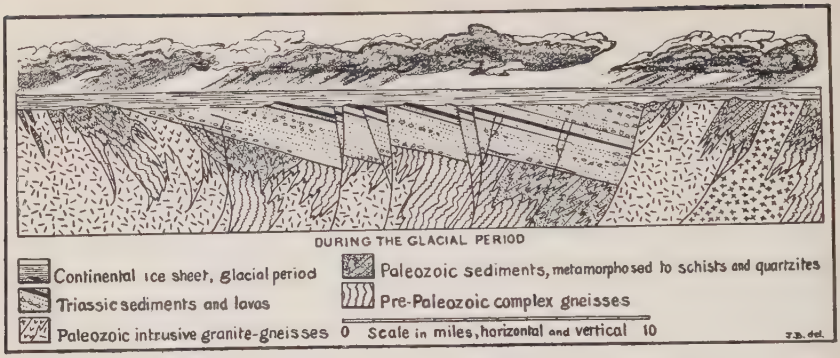

DURING THE GLACIAL PERIOD
Continental ice sheet, glacial period
Triassic sediments and lavas
Paleozoic intrusive granite-gneisses
Paleozoic sediments, metamorphosed to schists and quartzites
Pre-Paleozoic complex gneisses
0 Scale in miles, horizontal and vertical 10

FIG. 181. CONNECTICUT IN THE GLACIAL PERIOD.

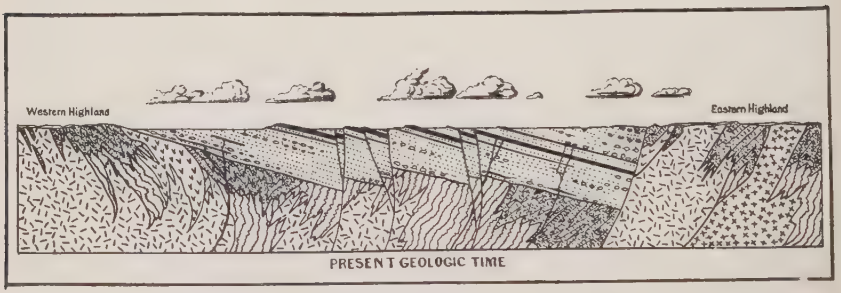


FIG. 182. CONNECTICUT AT PRESENT.

track is the projecting edge of a thick, harder layer of the basaltic lava that was erupted so long ago.

Similarly, the New York trains on the New Haven lines traverse this zone of special geological history. To the observer in the dining-car, the gentle New England landscapes give little suggestion that he is running over a region which was once a place of storm and stress. Until he has studied the geology, the observer could not dream that he is crossing the superposed roots of two different mountain chains, the younger built out of the ruins of the older; he could not know that the Connecticut Valley once saw volcanic action and felt the earth shake violently with the faulting and slipping of huge crust blocks, one against another.

But after the topography of Connecticut was established in very nearly its present form, the State underwent the remark-

able experience of the Glacial period. Through a change of climate the whole region became smothered under a crawling ice-cap, which over the Connecticut Valley had an average thickness of at least 2,000 feet (Figure 181). For many thousands of years this ice, streaming southward, scratched and grooved the solid rocks, removed the capping of soil and weathered rock which had accumulated in pre-Glacial time, and in places quarried away scores of feet of the fresh living rock beneath. When the ice melted away, much of this glacial detritus was left on the rock surface of the State, forming a thin veneer of gravel, sand, and clay. The veneer was too thin to change essentially the relief of Connecticut from the condition it had just before the Glacial period; hence the section of Figure 182, showing the present topography, is practically identical with that of Figure 180.

The story is complex enough, though the much longer history of the Connecticut Valley region *before* the Appalachian revolution has been hardly touched upon at all. Before we can claim a complete understanding of New England's evolution, we must have delved still deeper into the rocky records of geological events. Yet many of these older records are buried under the sandstones of the Connecticut Valley, and many other records, once written in the rocks, have disappeared during the course of age-long erosion.

These two examples will point the moral. *All* the writing in the rocks is needed for securing even an approximation to the full history of the earth. Because some of the records are destroyed or buried, the attempt to sketch the evolution of the face of the earth can be only in part successful. That fact shall not astonish us. What is astonishing is the tale which the young science of geology can tell us. The story, patiently read out of the rocks, is already full of fascinating incidents, as well established as they are significant. These many events, demonstrated and accepted by those competent to judge, form subject-matter of historical geology. But there remain a large number of weighty geological problems which have no accepted solutions. As yet

we can treat them only speculatively. This chapter is devoted largely to a speculative outline of the earth's history in its broader aspects.

At the outset one needs a proper cosmogony. How did the earth originate? What was it like before the oldest rock was formed? Quite clearly, all subsequent changes have been condi-

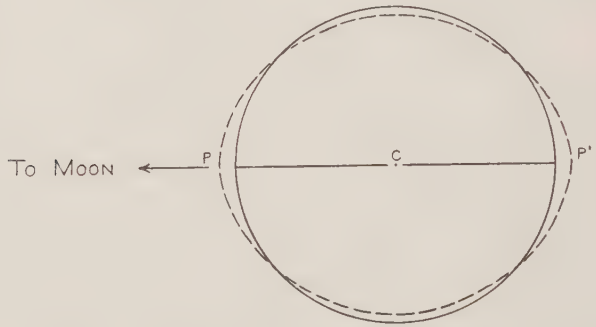


FIG. 183. TIDAL DISTORTION OF THE EARTH.

tioned by the properties of the earth at its initial stage. As usual with a good story, we begin at the beginning.

Professor T. C. Chamberlin, the geologist, has improved on the famous nebular hypothesis of Kant and Laplace concerning the origin of the solar system. Like the older masters, Chamberlin believes the earth to have been once part of the sun's body. His epoch-making contribution consists in suggesting how the matter of our planet was separated from the sun. The method was by *tidal disruption*.

Let Figure 183 refresh memory of a lesson in school. The earth without a lunar tide is represented by the full circle. The moon is on the line $P'CP$, the center of the earth being at C. The attraction of the satellite raises two tidal cones (broken curve) in the ocean on the earth. The attraction pulls out the sea-level figure of the earth, so that it becomes elongated in a line very nearly coincident with the line P-P'. Being more mobile, the ocean is pulled out more than the solid earth, but the solid earth really yields about one-third as much as the liquid

does. The difference in the amounts of yielding by ocean and crust conditions the existence of the ocean tides.

The tidal cones in the solid earth are very low, of the order of one foot in height. The distortion is small, because the moon is small and far away. Under the influence of the body tides, the city of Boston rises and falls every few hours, but we are not aware of it. The wave ridden by the city is 12,000 miles long, and of a height measurable in inches. The displacement of the crust is too slight to be noticed.

But what would happen if the attracting bodies were composed of hot gas, millions of times more massive than earth or moon, and relatively close together? In place of the earth, let us put the sun, already tending to expand because it was gaseous. In place of the moon, we imagine a star comparable to the sun itself in mass. If so powerful a body came near the sun, the tides in the sun would be correspondingly great.

The stars are all rapidly moving through space. They are widely separated. Yet their number is so great, their paths so diverse, that once in a long while one star may approach another closely. Professor Chamberlin assumed that a massive star made such a close approach to the sun. Though at no time less than some millions of miles away, the visiting star, as it raced past, must have created an enormous gravitational disturbance in the sun. The tides set up on the gaseous sun were many thousands of miles high. The gas of the tidal protuberance nearer the visiting star tended to stream away toward the visitor. According to the tidal-disruption theory, the protuberant gas did stream away in that direction. Whether or not there would be a similar tidal outrush of matter from the opposite side of the sun would depend on the size of the sun at the time. For the present purpose we need not decide this question. The principle of planetary genesis will be illustrated, while we concentrate attention on the body of gas that streams out on the side nearer the visiting star.

Assuming the star to approach the sun by what is technically called a "slow" encounter, Jeans, the English physicist, has

calculated what the shape of this outrushing protuberance would be. Figure 184 illustrates more definitely the condition for the instability of the sun. The heavy line represents the sun's shape as disturbed by the attraction of the visitor. When the visiting star had come close enough, this figure for the sun became unstable. Mathematical analysis shows that the solar gas must begin to stream toward the visitor in the direction of the sharp point of the tidally deformed solar mass of gas, the point being always directed straight at the visitor. Thus a long, thick filament of gas leaves the sun, traveling toward the visiting star.

FIG. 184. INSTABILITY OF THE SUN, RESULTING FROM A "SLOW" ENCOUNTER WITH ANOTHER STAR. (ACCORDING TO JEANS.)

From the diagram of Figure 185 we see how the shape and position of the filament will change as the visitor flies past. First we note the path of the star-visitor. When the visitor is at the position marked No. 1, the sun loses some of its mass and the filament has begun to grow. While the gas rushes out toward the visiting star, the visitor moves some distance on its path, here marked with the broken curved line. The star keeps pulling the gas toward itself and stimulates more solar gas to stream out, adding to the filament. When the visitor is at position No. 2, the emitting point on the sun is in its own position No. 2. Similarly with the star position No. 3 and the solar

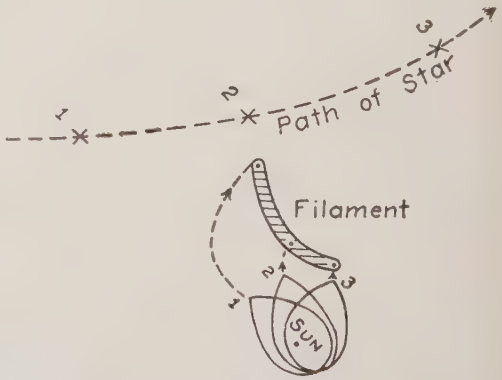


FIG. 185. THE SOLAR FILAMENT, THE ORIGINAL FORM OF THE PLANETARY SYSTEM. (ACCORDING TO JEANS.)

position No. 3. At this stage the escaping filament has attained the general shape of a boomerang, as shown with shading on the diagram.

Passing beyond some such point as that numbered 3, the star can no longer disrupt the sun; no more solar gas streams out.

The actual encounter of star and sun could hardly have been of the ideal "slow" kind, assumed by Jeans. Yet his analysis serves to show in principle how the tidal disruption of the sun would take place.

The visiting star must also have felt tidal effects. However, it is now so far away that the most powerful telescope could not tell us if the effects were the same as those permanently registered for the sun.

The solar filament was left out in space, but was still within the sun's gravitational power. Though the filament still obeyed the powerful outward impulse of the star, that impulse rapidly diminished with the star's speedy retreat into space. The sun's attraction grew relatively the greater. There was, therefore, a tendency for the filament to fall back into the sun. The combination of motions could not fail to cause the filament as a whole to revolve around the sun, to remain in that relation for an indefinitely long time.

Jeans has shown how the gaseous filament would, under its self-gravitation, break up into a number of balls, each revolving in its own orbit around the sun. These balls are the planets, including the earth.

Recently Jeffreys, another English physicist, has published an analysis of the tidal-disruption theory. In the main his conclusions resemble those of Jeans, but contain a more definite statement about the original condition of the earth as a separate body. Jeffreys points out that the planet would be gaseous for a few thousands of years. Radiation of heat finally led to a liquid stage, which also could not have lasted more than some thousands of years; for, at the end of this comparatively short time, the rapid radiation of heat must have caused the formation of a solid crust. With the exception that Jeffreys exagger-

ated somewhat the length of time during which the earth was liquid at the surface, his picture of the evolution seems to be the best of all.

We assume, then, a period during which our earth was a mass of hot gas and obviously much bigger than at present, though containing nearly the same amount of matter. During that period the earth's materials were sorted by gravity. The atoms of heavy iron sank to the center; the lighter elements, which were later to form silicates, that is, the compounds essentially making up common rocks and lavas, rose, and these elements were segregated in the form of a thick outer shell of gas. See Figure 60, page 108.

During the following, liquid stage, the silicate shell was covered with a continuous blanket of mixed air and water-gas or very hot steam. This residual gas had something like the mass of our present atmosphere and ocean, taken together. Its pressure on the liquid silicate shell was considerable, a few hundreds of atmospheres; hence much of the gas must have been dissolved in the silicate melt, just as carbon dioxide gas is dissolved in water under pressure. The newest cosmogony thus arrives at practically the same kind of primitive earth as that deduced from the old, classic nebular hypothesis of Laplace and Kant.

An isolated planet, which had been fluid for a very long time, would be likely to have taken on a shape and an internal arrangement of densities, both of which were closely adapted to the forces of gravitation and rotation. If such a body became crusted, there would be no notable differences of density corresponding to the case of a high-floating continent. There would be nothing to correspond to a land hemisphere, as opposed to a water hemisphere. The molten earth must have been a smooth earth, the surface of the liquid rock being everywhere level. If the earth's materials were symmetrically arranged around the polar axis, and if no outside force came into play, the superficial layer would freeze solid and make the floor of a universal ocean of nearly uniform depth. On this hypothesis there could be no continent, *no dry land whatever*, except, possibly, small volcanoes.

We are now face to face with a principal mystery of nature. Actually the earth's substance *is* differentiated into the form of continent overlooking deep ocean basin. That obvious, infinitely important fact, dry land on the continental scale, has to find its place in any theory of the earth. The problem is as difficult as it is fundamental. Very little has been published on it. We must try to find our way more or less in the dark.

Space permits of no more than a rapid statement of the best guess, the guess that seems at all promising. Yet a reasonable guess is better than the ruling degree of inactivity of scientific thought regarding the original dividing of the waters from the land. The suggestion to be offered is based on the principle that mountain structures are products of the sliding of continental blocks. We have seen each mountain structure to represent a local thickening of the lighter rocks, so that the surface of the chain comes to stand high above the general level of the earth's crust. In this fact have we a clue to the solution of the present problem? Were the comparatively light "granitic" rocks of the young earth more widely spread over its surface than they are at present? Were the rocks of the original "granitic" crust concentrated in one hemisphere by sliding, accompanied by folding, rafting, up-ending, and consequent thickening of light rocks in that hemisphere? If such concentration took place, and if the thickening of the light rocks were sufficient, the surface of the complex, deformed mass of "granitic" material would ultimately come to stand above the level of the sea; a land hemisphere would have been differentiated from a water hemisphere.

The ancient slidings could have occurred only on the condition that the crust of the young earth was not level. When the planet was molten at the surface, that surface was necessarily level. Presumably also the initial crust was level or nearly level. The suggested important deleveling of the granitic crust must have been, therefore, a later event. Since, by hypothesis, the sliding slopes were directed toward the center of the surface of one hemisphere, the globe is assumed to have become unsymmetrical after its solidification.

Such hemispherical asymmetry of the solid figure of the earth could result only from changes in the interior. If at first the great interior was hemispherically asymmetric with respect to density or temperature, or with respect to both of these properties, deep-seated flow tended to redistribute the internal materials, with consequent deleveling of the crust.

Even now the earth appears to be asymmetric in the sense demanded by the general hypothesis. According to the computations of Helmert and Heiskanen, the sea-level figure of the earth is not circular, but elliptical, in the plane of the equator. The longer axis of the ellipse passes through central Africa at 18 degrees east longitude and the middle of the Pacific basin at 172 degrees west longitude (Heiskanen). The longer axis of the ellipse is about 690 meters greater than the shorter axis. This means that there is excessive attracting matter in the sectors of the earth which include the longer axis of the ellipse. The internal asymmetry of the globe has evidently long existed, and is probably a remnant of the asymmetry that existed at the remote epoch just after the earth was molten at the surface.

The possible conditions leading to the internal asymmetry will now be considered. Three different sets of conditions are suggested. One of them derives from the assumption that the earth with its present mass was directly condensed from the gaseous state, the moon being at all times a separate body. The other two sets of conditions derive from the well-known hypothesis that the moon was formerly part of the terrestrial planet, and was thrown off by a kind of fission.

First, then, the asymmetry of the figure of the solid earth might be conceived to have been the ultimate product of an internal asymmetry which was produced during the condensation from the gaseous state. As already stated, the condensation to a liquid was a relatively quick process. We imagine the more or less irregular assembling of materials varying in density. We note that, toward the center of the growing ball, the increasing pressure could not fail to develop high viscosity, no matter how fluent the molten rock of the surface might be. Because of

that viscosity, the earth's internal layers of equal density would long be prevented from becoming level. Thus the rate of increase of density in one hemisphere, from the surface downward, would be different from the rate of increase of density in the opposite hemisphere.

Such hemispherical asymmetry of the internal shells meant internal stress. By flow of material each shell of uniform density tended to become dead level. The tendency was resisted by the strong viscosity of the interior. Hence some of this initial asymmetry of the interior shells was annulled only long after the crust was formed on the earth. During the later adjustment the crust in the one hemisphere would sink, and the crust in the opposite hemisphere would rise. The result would be distortion of the earth's external form, hemispherical asymmetry for the rocky figure.

We now turn to the other two suggestions, both involving the problem of the moon's origin.

Two master mathematicians have attacked this problem, and each has published an explanation of our moon. Each explanation assumes the moon to have been at one time a part of the planet, and to have been separated catastrophically when the young planet was rotating very rapidly.

The one solution to the problem is due to Henri Poincaré. He showed that a liquid planet, rotating at a certain high speed, would take on a pear-shaped figure, which would be stable for that speed. If, however, the rotational velocity were slightly increased, the small end of the pear would break off and, as an independent body, would revolve around the center of gravity that is common to both parts of the original mass. Poincaré suggested this origin for the moon. Some authorities think that the earth could never have rotated fast enough to become so unstable. Their objection has weight, but it is not conclusive. Poincaré's hypothesis seems still to represent one of the possibilities, especially so if the young earth was explosive.

The other solution to the lunar problem is that of another prince among the mathematical physicists, George H. Darwin. He also assumed the moon to be a daughter of the earth. Ac-

cording to Darwin, the forces determining the break-up of the original earth were two in number. The more powerful of these was the centrifugal force due to the earth's rapid rotation. The second, less directly powerful but no less essential, was the tidal force which was exerted on the planet by the sun. The tidal force was feeble, but Darwin showed how its effects might have been built up so as to cause the original earth to break into large fragments. The catastrophic accumulation of effects was attributed to the principle called "resonance." Without describing the mechanism of resonance, I shall here merely note its practical effect, according to Darwin. The mechanism worked to the point of producing a tidal wave in the molten earth, which was of the order of 1,000 kilometers in height. When the leaping tide had reached such a height, its acceleration was enough to cause one or more large pieces of the planet to jump clear away from the main body. The matter, thus propelled out of the original earth, had its own center of gravity. Around that center the ejected matter pulled itself together, by its own gravitation, into a nearly spherical form and began an independent career as our moon.

Darwin's theory of the moon has its troubles. One of these is the difficulty of believing that the molten planet was mobile enough to permit of the making and unmaking of a 1,000-kilometer tide every few hours. The rigidity and viscosity of the deeper, greater part of the planet were, because of pressure, not very different from their values at the present day. Yet we must think of the leaping tide as in part built up from material derived from relatively deep layers in the earth.

In spite of this serious difficulty Darwin's suggestion, like that of Poincaré, probably should still be retained among the working hypotheses of the moon's origin.

To summarize. We have found three conceivable causes for hemispherical asymmetry in the distribution of the internal materials of the molten earth. The asymmetry may have developed on account of the speed with which the gaseous earth was liquefied. Secondly, the asymmetry may have developed when the

moon was torn out of the side of the earth, according to Poincaré's hypothesis. Thirdly, the asymmetry may have developed in consequence of the similarly catastrophic fission imagined by Darwin. The cause of the asymmetry is an open problem; yet, partly because the earth is still somewhat out of equilibrium (Helmert and Heiskanen), it is not absurd to assume hemispherical asymmetry for the earth's interior when the globe was molten at the surface.

We have seen that such internal asymmetry would long persist in the sluggish, viscous interior. Chapter V contains some illustrations of the slowness with which the earth recovers from distortion and returns to a condition of balance after that balance has been disturbed in any way. The deep-seated flow, correcting for any departure from perfect balance or equilibrium, is proved to have gone on for many thousands of years.

Long before the internal asymmetry could have been annulled by deep flow, the earth would have been crusted, for the crusting would occupy only a few centuries. It is expedient to note the process of crusting, for we shall see that by its very nature this process must have soon reached completion.

Because of the rapid radiation of heat from the molten surface, the temperature there fell to that at which crystals began to form, much as crystals of sugar grow in a cooling syrup. The crystals of the earth's superficial layer were denser than the surrounding, residual melt, and, either singly or in groups as flakes of solid matter, they sank. New hot liquid rose to take their places. Radiation quickly chilled this other liquid to the temperature of crystallization, with additional subsidence of the solids. And so on, in succession. The sunken solids reached a moderate depth, where their density was matched. At those levels they were remelted, lowering the temperature of the liquid. Thus a superficial shell of the earth became rapidly cooled by a kind of convection. With sufficient convection and cooling, sunken solids could no longer be remelted. These remained solid. Others joined them. Ultimately a solid, continuous, crystalline crust was developed over the globe. During the crusting, the

original liquid at the surface must have differentiated into layers. For technical reasons it seems probable that at this time the differentiation went so far as to form two layers—the lighter, of granitic composition, above; the denser, of basaltic composition, beneath.

Though the solid granitic layer may at first have covered the whole earth, it would be specially thick in one hemisphere of the unsymmetrical earth. At the same time most of the initial asymmetry of the deep interior would have persisted.

Computation shows that the crusting should have been completed within a few scores or hundreds of years after the earth attained the liquid state, or after the catastrophic fission of the moon. Hence the leisurely correction of the internal asymmetry would go on long after the mobility of the surface material had become very slight. In accordance with the reasoning described above, in connection with the first of the three basal hypotheses, the deep flow that tended to annul the internal asymmetry must induce further hemispherical asymmetry for the rocky figure of the earth. The crust would come to stand yet higher in the one hemisphere than in the other.

Later developments may be described in a similarly speculative manner. As the crust sank in the one hemisphere and rose in the other, the ocean, which had already been condensed from the primitive atmosphere, attained maximum depth in the former hemisphere. Under the extra weight of water, the corresponding sector of the earth was compressed more than the opposite sector. This would mean some additional deepening of the new ocean basin, and accentuation of the asymmetry of the earth's shape. It is even conceivable that the adjustments led to the formation of a single continent, a land hemisphere; and a single ocean basin, a water hemisphere.

If such deleveling of the crust became sufficiently advanced, the higher crust would tend to slide into the opposite hemisphere. If Asia and America slid toward the Pacific in relatively modern times, it is logical to inquire if the earliest high-standing continent did break up and slide toward the antipodal region, crum-

pling the rocks as it moved. Dare we think of extensive sliding, so that the whole of the granitic crust was ultimately concentrated in one hemisphere? If it was, then it must have been greatly deformed, greatly mountain-built. In fact, we can imagine more than one such oscillation of the earth's rocky figure, each adding to the complexity of the crustal structure.

In the sixth chapter we learned that the ancient Basement Complex of every one of the existing continents bears the marks of intense crumpling of its rocks. This crumpling or folding is similar to the folding represented in the much more modern mountain ranges. The complexes, which form the bulk of the existing continents, are mountain-structured. If crustal sliding and foundering can explain the folding and mashing-together of ordinary mountain ranges, then the older crumpling of the complexes may possibly be explained in the same way. At any rate, this seems to be one of the most promising clues to be followed in the attempt to account for the immense deformation of the oldest and most extensive formations of rock.

The hypothesis has other bearings. It explains the very existence of dry land. The continental surfaces now stand so high, because the granitic crust was folded and rafted together, and therefore thickened; and, secondly, because the rocks thus aggregated are specially light rocks. To-day each continent floats higher than the denser, heavier basaltic crust under the ocean. The sliding hypothesis has no small advantage, as it gives some kind of answer to the primary question: Why is there any dry land at all? I know of no other answer that appears valid.

Not only so. The hypothesis sketched demands that there came to be one, and only one, continent, formed by very ancient slidings. Geologists have found many proofs of the relative youth of the Atlantic, Arctic, and Indian Ocean basins. Land-animals, dinosaurs, could formerly walk from America to Europe and Africa; from Antarctica to Africa, and to Australia, and to America; from Australia to Asia. In fact, at the opening of the Paleozoic Era there seems to have been no essential break in the continuity of the continental plateau of the globe. Shallow seas

came and went on this single, unique continent, but the broad plateau long persisted, intact, even under the camouflaging thin sheets of sea water.

Since that time, according to the speculation outlined in the last chapter, the single continent was torn into the fragments

FIG. 186. WORLD-MAP, SHOWING THE OUTLINES OF THE CONTINENTAL MASSES AT THE 100-FATHOM (OR 200-METER) LINE OF DEPTHS IN THE OCEAN. (From Wegener's "Origin of Continents and Oceans," E. P. Dutton and Company, New York.)

that are represented by the existing continents and their satellitic islands. Figure 186 shows the outlines of the present continents, as marked by the 100-fathom line out to sea; for the edge of each continental plateau really drops off into deep water near the 100-fathom line, not at the actual shore-lines.

Reviewing the problem of the primitive continent, the reader can not fail to appreciate the uncertain basis on which the foregoing speculation is founded. The earth is surely unsymmetrical now, with an approach to a division into a land hemisphere and a water hemisphere. Is this asymmetry an inheritance from an original asymmetry in the distribution of the terrestrial matter

when the earth was molten at the surface? Or from an asymmetry determined by the loss of the moon's substance? Some emphasis has been placed upon the guess that the fission of earth and moon was the vital factor; yet we have found difficulty in seeing just how the fission could have taken place. Difficulties, no less weighty, stand in the way of full belief that practically all of the superficial "granitic" shell of the earth would, by sliding, accumulate in one hemisphere. The root of this part of the speculation lies in the similarity between the structure of ordinary mountain chains and the structure of the Basement Complexes. As Wegener himself has seen, it is natural to raise the question whether the early, wholesale deformation and thickening of the lighter rocks of the earth's crust have been due to the same kind of process as that represented in the crumpling and thickening of mountain rocks. If the landslide explanation for the younger mountain chains were proved, we could hardly escape the necessity of trying to frame a similar explanation for the complexly deformed rocks that constituted the primitive continent. Clearly the idea of continental migration is important also in the problem of the dry land.

Where so much is uncertain, further speculation is demanded, to guide the search for relevant facts. For example, were the light "granitic" rocks accumulated in one hemisphere by a kind of convection in the young earth? Were differences of density developed that caused slow-descending currents around a point near the earth's equator, rising currents at the antipodes, and horizontally directed currents between those points? If so, we could conceive: that the "granitic" rocks would be dragged passively into the hemisphere with the descending current; that "drag" folds, thrusts, and up-ending of blocks would characterize the rocks of that hemisphere; and that ultimately the light rocks would be sufficiently concentrated to make the primitive continent. In fact, some geologists have suggested an origin of the younger mountain chains in such convective movements among the deep materials of the globe. The landslide hypothesis, which has been specially stressed, itself implies a certain

amount of convective, radial movement of the earth's materials. Perhaps in the formation of the primitive continent, convection currents below the crust co-operated powerfully with the more or less independent sliding of the crust on the substratum.

As we begin a very brief sketch of some leading events in the later, better-known part of the earth's evolution, it will be of advantage to glance at Table XV, giving the names of the chief eras into which geological time has been divided.

TABLE XV

GEOLOGICAL ERAS

	APPROXIMATE DURATION IN MILLIONS OF YEARS (BARRELL)
Cenozoic Era	55
Mesozoic Era	135
Paleozoic Era	360
Pre-Paleozoic Eras	1,200
Pre-geological Eras	?

The relative ages of rocks are determined through fossils. Geological time has been divided on the basis of the kinds of organisms that lived during the different eras. So we have the Cenozoic Era, the era of recent life; that is, the period during which organisms, fundamentally allied to living animals and plants, were in existence and slowly evolving. Earlier still was the Mesozoic Era, the middle time of world-life, an era during which the animals and plants were strikingly different from the later Cenozoic types, and also strikingly different from the organisms of the still older Paleozoic Era, the time of ancient life.

Before the Paleozoic was an immense time, probably longer than all the three named eras put together. This oldest division of geological time includes the pre-Paleozoic eras. The rocky strata, then laid down, carry no abundant fossils, no more than obscure traces of life.

How long was each era? By a half-dozen methods, mutually corroborative, geologists have proved that each was very long, measurable in tens of millions of years. Through a wonderful

discovery we are able from the radioactivity of minerals to compute their age in years, so closely that, for philosophical purposes, we can date the formations in which the minerals occur. Joseph Barrell was one of those who have concerned themselves with the subject. Table XV includes his estimates of the duration of the different eras. Whatever changes this table may undergo with the progress of science (the estimate for the pre-Paleozoic eras may be somewhat too generous), it seems certain that the age of the earth and the ages of its various rock-formations can not have different orders of magnitude from the values of Barrell's table.

Now let us run quickly through the history of the globe since its primitive single continent was completed. For simplicity of statement, a rigorous distinction between the ascertained facts of geology and the many speculative considerations of the foregoing chapters will not be made. The reader himself has already savored the uncertainty which must attend any effort to sketch the earth's development. He may be able once more to forgive apparent dogmatism in the description.

The continent-wide deformation of the crust, seen in the crumpled Basement Complex, was a prolonged process of the earliest pre-Paleozoic eras. The deforming process began something like a billion years ago. Then the earth was young; then most alive; then the crust was most unstable.

Following the last paroxysmal sliding-together of the rocks and the formation of the unique continent, there was a long peace, so far as mountain-building was concerned. During that time of crustal repose, the continent was being domed and furrowed according to the process described in the last chapter. See Figures 153, 164, and 165, pages 243, 264 and 267. Then, after some preliminary skirmishes, a major battle was fought between gravity and the strength of rocks, the victory falling to gravity. At the close of the Paleozoic Era, about 200,000,000 years ago, the east-west geosyncline of the northern hemisphere was intensely crumpled by the sliding-together of the North Polar dome and the Equatorial dome. The result was

the Appalachian-Hercynian system of mountains, extending from west of Arkansas, through Alabama, New England, Newfoundland, Britain and France, Germany, Russia, and all across Asia to China. It was a colossal, probably uninterrupted, chain of mountains all the way.

A little later a similar meridional sliding crumpled the east-west geosynclinal prisms of the mid-latitude belt of the southern hemisphere, forming the mountain system now fragmentarily represented in the ranges of Argentina, South Africa, and Australia. See Figure 169, page 281.

Meantime, the old unique continent was being domed, *as a whole*. In this way sliding-slopes, directed toward the primitive Pacific Ocean, which was then larger than now, were generated. Simultaneously the geosynclinal prisms were thickening along the Pacific shores. Hence along those shores the crust was being weakened, along a belt 25,000 miles long.

At last, about the middle of the Mesozoic Era, scores of millions of years ago, the unique continent finally succumbed to the pull toward the Pacific. It broke into huge fragments, the Americas, Eurasia-Africa, Australasia, and Antarctica. The last, Antarctica, seems not to have moved much horizontally. The others slowly slid, with haltings and renewed sliding, toward the Pacific. The great mountain arcs of the Circum-Pacific Zone were born and slowly gained in strength as the continental fragments slipped down over the earth's body.

During the process of folding along the border of the invaded Pacific, basaltic floods were pouring out through the tension-cracks of the continental interior. The fissures, through which the lavas rose, became sealed with frozen basalt. Many fissures and lava floods were added. A new, heavy, deep-lying crust became ready to receive the water running in from the ancient Pacific Ocean; the Atlantic, Arctic, and Indian Oceans thus came into being, and were enlarged to an unknown extent by the subsidence of small blocks of the fractured continent. The floods of basaltic lava in Greenland, Iceland, the Scottish isles, Argentina, South Africa, and India, are visible products of

these crustal tensions, well inside the limits of the primitive continent. For examples see Figure 61, page 117; Figure 73, page 135.

Another grand testimony to the former prevalence of tension in the heart of the unstable primitive continent is the existence of the Atlantic type of coast-line. Its cracked, almost mountainless character stands in utter contrast with the Pacific type of coast-line. We have seen that the Atlantic type characterizes the three younger ocean basins. None is inclosed by mountain chains, like those so wonderfully framing the Pacific. Earth has no more significant contrast among its surface forms. See Figures 169–170, pages 281, 283.

So great a disturbance could not fail to bring new forces into play. Their combination with other forces, that had been long accumulating, caused Eurasia to be crushed into the Afro-Indian remnant of the primitive continent. Hence the Alpine-Himalayan chain was formed. A similar meridional sliding-together of the Americas formed the east-west Antillean-Central American system of mountains. See Figure 135, page 215; Figure 152, page 235; Figures 169–170, pages 281, 283.

These last intense movements began in the middle of the Cenozoic Era, perhaps 25,000,000 years ago. The dramatic process of building our existing mountains of the Alpine type lasted long, a large fraction of the 25,000,000 years, but, like Shakespearian drama, reached its climax in the act just before the last.

The last act has been one of necessary adjustments of the earth's crust. This second crumpling of rocks, overthrusting, and foundering in the east-west Mediterranean Zone of the northern hemisphere meant the sliding transfer of great masses of rock into the folded belt. The rafted-together, heavy masses were, in a measure, stiff. The body of the earth beneath them is, in a measure, stiff or rigid. It has taken much time for the crustal blocks, so tumultuously jammed together and piled one on another, to settle into equilibrium; that is, to reach a state of rest. Through the last few millions of years, the mountain

rocks of Central America, West Indies, Alps, and European Mediterranean, Caucasus, Persia, India, and China, have been settling down, trying to reach a state of perfect ease in their new setting. Along this zone of the earth the rocks are, therefore, breaking, snapping, slipping on the planes of fracture or faults. Each time they suddenly break, one block moving feet or inches past its neighbor, there is an earthquake.

During the Cenozoic Era there was similar building of mountains in the zone around the Pacific, which, for the second time, has felt the encroachment of Eurasia and Australasia at least. Here, too, the readjustments have been accompanied by faulting or earthquakes.

So we come back to our first illustration of the earth's mobility, to earthquakes. Now we see why strong earthquakes are so largely confined to the east-west, mid-latitude zone of the northern hemisphere and to the Circum-Pacific Zone. The shaded areas of Figure 2, page 6, show where mankind feels oftenest and most intensely the dreaded earthquakes. These shaded belts might almost serve also as a rough diagrammatic map of the two world zones of young, rugged, lofty chains of mountains. Possibly some of the shocks originating in the two zones are due to a continuance of the slow mountain-building, locally, at the present day.

Again, the readjustments in the two folded zones have developed fractures clear through the solid crust of the earth. Hence lava has risen from the substratum along these fissures, causing volcanoes at intervals all around the Pacific and along much of the Mediterranean Zone of high mountains. From Patagonia to Alaska; from Alaska to Japan; from Japan, through the Philippines, to New Zealand—all around the ancient ocean—runs the long chain of volcanoes, active or recently extinct, the so-called "Circle of Fire."

In the Mediterranean Zone we think of the Mexican Colima, Popocatepetl, and Orizaba. In the West Indies we recall Soufrière and the tragedy of Saint-Pierre, with its 30,000 inhabitants annihilated by the frightful explosion of Mont Pelée in 1902.

Then Madeira, Azores, Stromboli, Etna, Vesuvius, Santorin, Kasbek and Elburz of the Caucasus, and Ararat — all these are but sample by-products of the last powerful mountain-making along the Mediterranean Zone.

And we recall that the second principal cause for the vol-

Photograph by Vittorio Sella.

FIG. 187. A VIEW IN THE KARAKORUM HIMALAYA.
Heights in feet.

canic eruption of the past was the tearing open of the crust on the up-stream edges of the continents which slowly slid, crumpling the rocks, down-stream, into mountain chains.

Finally, we note again the other significant part of the readjustments in each of the two world zones of mountains: namely, massive, broad upheaval long after the folding. This it is which has given mountain torrents their chance to dig deep their gorges and canyons. Because of these bodily upheavals to great heights, glaciers have been born. And it is chiefly to the

quarrying, rasping, eroding glaciers that we owe the marvelous sculpturing of Swiss and New Zealand Alps, of Rocky Mountains, of Himalaya and Tibet—the Roof of the World. Rivers, glaciers, wind, and waves are now busy, carving out the smaller, yet gloriously impressive, features of the Face of the Earth (Figure 187). That face is lined, scarred, of infinitely complex lineaments. Our earth is very old, an old warrior that has lived through many battles. Nevertheless, the face of it is still changing, and science sees no certain limit of time for its stately evolution.

Our solid earth, apparently so stable, inert, and finished, is changing, mobile, and still evolving. Its major quakings are largely the echoes of that divine far-off event, the building of our noble mountains. The lava floods and intriguing volcanoes tell us of the plasticity, mobility, of the deep interior of the globe. The slow coming and going of ancient shallow seas on the continental plateaus tell us of the rhythmic distortion of the deep interior—deep-seated flow and changes of volume. Mountain chains prove the earth's solid crust itself to be mobile in high degree.

And the secret of it all—the secret of the earthquake, the secret of the "temple of fire," the secret of the ocean basin, the secret of the highland—is in the heart of the earth, forever invisible to human eyes.

SUGGESTED WORKS OF REFERENCE

To indicate the best works for further reading on the broad topics of this book is a difficult task. The following list is not intended to cover fully the more valuable writings. The aim of the compilation has been double: first, to name books and articles which themselves furnish references to the vital publications; secondly, to mention certain papers which deal with special elements in the theory of the earth here presented.

In the first group of titles the most important book is Emm. de Margerie's French translation of "Das Antlitz der Erde," the amazing life-work of Eduard Suess. Monsieur de Margerie has not only produced a perfect translation of that greatest of geological syntheses, but has added hundreds of maps and sections and thousands of bibliographic references; so that this edition of Suess is the vade mecum for any one who wishes to plunge into the important geological literature of the whole earth. For seismology the corresponding treasury of information is A. Sieberg's "Erdbebenkunde," unfortunately not yet translated into English. For the subject of igneous action or volcanism in the broader sense, abundant references to original sources are distributed through the pages of J. P. Iddings's "Igneous Rocks" (New York, 1909–1913), of F. von Wolff's "Der Vulkanismus" (vol. 1, Berlin, 1914), and of my own "Igneous Rocks and Their Origin" (New York, 1914).

Each of the theories of crustal warping, mountain-building, cosmogony, and the earth's interior already has a huge bibliography, but for the needs of the present day no general work on any of these topics stands out as particularly strong in guiding to the best literature. In connection with the actual theses of the present volume, the reader may find some guidance to the underlying facts by using the references in my own more technical papers. For that reason and also because they give data on

which the arguments of this book are founded, these technical papers are listed in the sequel.

The standard text-books and larger manuals of geology are naturally important records of many of the facts and ideas here described. The number of excellent, comparatively elementary text-books is considerable, including: H. F. Cleland's "Geology, Physical and Historical" (New York, 1923); the "Text-book of Geology," by L. V. Pirsson and C. Schuchert (2d edition, New York, 1920–1924); and W. B. Scott's "Introduction to Geology" (New York, 1906).

Among the leading modern manuals of geology are: "Geology," by T. C. Chamberlin and R. D. Salisbury (3 vols., New York, 1906); A. Geikie's "Text-book of Geology" (2 vols., 4th edition, London, 1903); A. W. Grabau's "A Comprehensive Geology" (New York, 1920); E. Haug's "Traité de Géologie" (2 vols., Paris, 1907–1911); and E. Kayser's "Lehrbuch der Geologie" (2 vols., Stuttgart, 1918–1921).

The more specific references for the different chapters of this book follow.

CHAPTERS I AND II

Brigham, W. T., "Historical Notes on the Earthquakes of New England, 1638–1869" (*Memoirs, Boston Society of Natural History*, vol. 2, 1871).

Close, U., and McCormack, E., "When the Mountains Walked" (*National Geographic Magazine*, vol. 41, 1922, p. 445).

Davison, C., "The Japanese Earthquake of 1 September, 1923" (*Geographical Journal*, vol. 65, 1925, p. 42); "A Study of Recent Earthquakes" (London, 1905).

Dutton, C., "The Charleston Earthquake of August 31, 1886" (*Ninth Annual Report, United States Geological Survey*, 1888, p. 209).

Earthquake Investigation Committee, Tokyo: *Publications*, 1897–1907; *Bulletins*, 1907 to date.

Fuller, M. L., "The New Madrid Earthquake [in the Mississippi Valley], 1811–13" (*Bulletin* 494, *United States Geological Survey*, 1912).

Gilbert, G. K., and Others, "The San Francisco Earthquake and Fire of April 18, 1906" (*Bulletin* 324, *United States Geological Survey*, 1907).

Hobbs, W. H., "Earthquakes" (New York, 1907).

Jaggar, T. A., "The Yokohama-Tokyo Earthquake of September 1, 1923" (*Bulletin, Seismological Society of America*, vol. 13, 1923, p. 124).

Jeffreys, H., "The Earth" (Cambridge, England, 1924, Chapter 12).

Katô, T., "Preliminary Notes on the Kwantô [Tokyo] Earthquake in Japan, September 1, 1923" (*Journal, Geological Society of Tokyo*, vol. 30, 1924, p. 17).

Knott, C. G., "The Physics of Earthquake Phenomena" (Oxford, 1908).

Lawson, A. C., and Others, "Report on the California Earthquake of April 18, 1906" (*Publication No.* 87, *Carnegie Institution of Washington*, vol. 1, with atlas, 1908).

Milne, J., "Seismology" (London, 1898); "Earthquakes" (5th edition, London, 1903).

Montessus de Ballore, F. de, "Les Tremblements de Terre. Géographie Séismologique" (Paris, 1906); "La Science Séismologique" (Paris, 1907); "La Géologie Sismologique" (Paris, 1924).

Oldham, R. D., "Report on the Great Earthquake of June 12th, 1897" (*Memoirs, Geological Survey of India*, vol. 29, Calcutta, 1899).

Reid, H. F., "Report on the Mechanics of the California Earthquake of April 18, 1906" (*Publication No.* 87, *Carnegie Institution of Washington*, vol. 2, 1910).

Seismological Society of America, *Bulletins*, 1911 to date.

Sieberg, A. (with B. Gutenberg), "Erdbebenkunde" (Jena, 1923).

Suda, K., "On the Great Japanese Earthquake of September 1st, 1923" (*Memoirs, Imperial Marine Observatory, Kobe*, vol. 1, no. 4, 1924).

Tarr, R. S., and Martin, L., "Recent Changes of Level in the Yakutat Bay Region, Alaska" (*Bulletin, Geological Society of America*, vol. 17, 1906, p. 29); "The Earthquakes at Yakutat Bay, Alaska, in September, 1899" (*Professional Paper, United States Geological Survey*, no. 69, 1912).

CHAPTER III

Adams, L. H., "Temperatures at Moderate Depths within the Earth" (*Journal, Washington Academy of Sciences*, vol. 14, 1924, p. 459).

Adams, L. H., and Washington, H. S., "The Distribution of Iron in Meteorites and in the Earth" (*Journal, Washington Academy of Sciences*, vol. 14, 1924, p. 333).

Bowie, W., "Investigations of Gravity and Isostasy" (*Special Publication No.* 40, *United States Coast and Geodetic Survey*, Washington, 1917).

Chamberlin, T. C., "The Origin of the Earth" (Chicago, 1916); (with R. D. Salisbury), "Geology" (3 vols., New York, 1906, especially vols. 1 and 3).

Clarke, F. W., "Data of Geochemistry" (5th edition, *United States Geological Survey, Bulletin* 770, 1924).

Daly, R. A., "Igneous Rocks and Their Origin" (New York, 1914); "The Earth's Crust and Its Stability" (*American Journal of Science*, vol. 5, 1923, p. 349); "Relation of Mountain-building to Igneous Action" (*Proceedings, American Philosophical Society*, vol. 64, 1925, p. 283).

Gutenberg, B., "Der Aufbau der Erde" (Berlin, 1925).

Hayford, J., and Bowie, W., "The Figure of the Earth and Isostasy from Measurements in the United States" (*Publication of the United States Coast and Geodetic Survey*, 1909).

Holmes, A., "Radioactivity and the Earth's Thermal History" (*Geological Magazine*, vol. 52, 1915, pages 60 and 102; vol. 62, 1925, pages 504 and 529).

Jeffreys, H., "The Earth" (Cambridge, England, 1924, Chapters 1–6, 9).

Joly, J., "Radioactivity and Geology" (London, 1909); "The Surface-History of the Earth" (Oxford, 1925).

Krige, L., and Pirow, H., "Temperature Measurements in the Dubbledevlei Borehole, Carnarvon District" (*Transactions, Geological Society of South Africa*, vol. 26, 1923, p. 50).

Thomson, W., and Tait, P. G., "Treatise on Natural Philosophy" (Cambridge, England, vol. 1, part 2, 1883).

Washington, H. S., "The Chemistry of the Earth's Crust" (*Journal, Franklin Institute*, vol. 190, 1920, p. 757).

Williamson, E. D., and Adams, L. H., "Density Distribution in the Earth" (*Journal, Washington Academy of Sciences*, vol. 13, 1923, p. 413).

CHAPTER IV

General References. (See page 321.)

Dana, J. D., "Characteristics of Volcanoes" (New York, 1891).

Geikie, A., "Ancient Volcanoes of Great Britain" (2 vols., London, 1897).

Harker, A., "The Natural History of the Igneous Rocks" (New York, 1909).

Hitchcock, C. H., "Hawaii and Its Volcanoes" (Honolulu, 1909).

CHAPTER V

Daly, R. A., "Pleistocene Changes of Sea-level" (*American Journal of Science*, vol. 10, 1925, p. 281); "The Glacial Control Theory of Coral Reefs" (*Proceedings, American Academy of Arts and Sciences*, vol. 51, 1915, p. 158); "A Recent World-wide Sinking of Ocean-level" (*Geological Magazine*, vol. 57, 1920, p. 246).

Geikie, A., "Text-book of Geology" (on changes of level at page 377, vol. 1, 4th edition, London, 1903).

Schuchert, C., "Paleogeography of North America" (*Bulletin, Geological Society of America*, vol. 20, 1910, p. 427); "Sites and Nature of the North American Geosynclines" (*Bulletin, Geological Society of America*, vol. 34, 1923, p. 151).

Willis, B., "Paleogeographic Maps of North America" (*Journal of Geology*, vol. 17, 1909, pages 203, 253, etc.).

Wright, W. B., "The Quaternary Ice Age" (London, 1914).

CHAPTER VI

Argand, E., "Sur l'arc des Alpes Occidentales" (*Eclogæ Geologicæ Helvetiæ*, vol. 14, no. 1, 1916); "La Tectonique de l'Asie" (Congrès géologique internationale, XIII^e^ session, 1922, pages 171–372).

Cadell, H. M., "Experimental Researches in Mountain Building" (*Transactions, Royal Society of Edinburgh*, vol. 35, 1888, p. 337).

Heim, A., "Geologie der Schweiz" (2 vols., Leipzig, 1921).

Peach, B. N., and Horne, J., "The Geological Structure of the North-west Highlands of Scotland" (*Memoir of the Geological Survey of Great Britain*, 1907).

Staub, R., "Der Bau der Alpen" (*Beitraege zur Geologischen Karte der Schweiz*, Neue Folge, Lieferung 52, 1924).

Suess, E. (translation by E. de Margerie), "La Face de la Terre" (3 vols., Paris, 1897–1918).

Willis, B., "Stratigraphy and Structure, Lewis and Livingston Ranges, Montana" (*Bulletin, Geological Society of America*, vol. 13, 1902, p. 305); "The Mechanics of Appalachian Structure" (*Annual Reports, United States Geological Survey*, vol. 13, part 2, 1893, p. 217).

CHAPTER VII

Arldt, T., "Die Entwicklung der Kontinente und ihrer Lebewelt" (Leipzig, 1907).

Daly, R. A., and Molengraaff, G. A. F., "Structural Relations of the Bushveld Igneous Complex, Transvaal" (*Journal of Geology*, vol. 32, 1924, p. 1).

Daly, R. A. (See references for Chapter III), "Decrease of the Earth's Rotational Velocity and Its Geological Effects" (*American Journal of Science*, vol. 5, 1923, p. 372).

Darwin, G. H., "The Tides" (3d edition, London, 1911); "Tidal Friction and Cosmogony," vol. 2 of "Scientific Papers" (Cambridge, England, 1908).

Gilbert, G. K., "Report on the Geology of the Henry Mountains" (Washington, 1877).

Groll, M., "Tiefenkarte der Ozeane" (*Veröffentlichungen des Instituts für Meereskunde, Neue Folge A, geographisch-naturwissenschaftliche Reihe*, Heft 2, Berlin, 1912, with maps).

Kober, L., "Der Bau der Erde" (Berlin, 1921); "Lehrbuch der Geologie" (Vienna, 1923).

Murray, J., Address on "Oceanography" (*Geographical Journal*, vol. 14, 1899, p. 426, with map).

Schuchert, C. (See references for Chapter V.)

Staub, R. (See references for Chapter VI.)

Suess, E. (See references for Chapter VI.)

Taylor, F. B., "Bearing of the Tertiary Mountain Belt on the Origin of the

Earth's Plan" (*Bulletin, Geological Society of America*, vol. 21, 1910, p. 179).

Weed, W. H., and Pirsson, L. V., "Geology and Mineral Resources of the Judith Mountains of Montana" (*Annual Reports, United States Geological Survey*, vol. 18, part 3, 1898, p. 445).

Wegener, A., "Die Entstehung der Kontinente und Ozeane" (3d edition. Braunschweig, 1922; well translated by J. G. A. Skerl as "The Origin of Continents and Oceans," London, 1924).

CHAPTER VIII

Barrell, J., "Central Connecticut in the Geologic Past" (*Bulletin 23, Geological and Natural History Survey of Connecticut*, 1915).

Chamberlin, T. C. (See references for Chapter III.)

Darwin, G. H. (See references for Chapter VII.)

Fisher, O., "Physics of the Earth's Crust" (2d edition, London, 1889, p. 336).

Heiskanen, W., "Untersuchungen über Schwerkraft und Isostasie" (Helsingfors, 1924; full abstract by W. D. Lambert in *American Journal of Science*, vol. 10, 1925, p. 82).

Jeans, J. H., "Problems of Cosmogony and Stellar Dynamics" (Cambridge, England, 1919); "The Origin of the Solar System" (*Nature*, vol. 113, 1924, p. 329); "The Nebular Hypothesis and Modern Cosmogony" (Halley Lecture, Oxford, 1923).

Jeffreys, H., "The Earth" (Cambridge, England, Chapters 3 and 14).

Moulton, F. R., "An Introduction to Astronomy" (new edition, New York, 1919).

Poincaré, H., "Leçons sur les Hypothèses Cosmogoniques" (Paris, 1913, p. 189).

Wegener, A. (See references for Chapter VII).

Willis, B. (See references for Chapter V.)

Young, C. A., "A Text-book of General Astronomy" (Boston, 1889).

INDEX

Abyssal-injection theory of volcanoes, 134 *ff.*, 149, 160, 278
Acapulco, Mexico, sea waves of 1909 shock in, 41
Acceleration of particles in earthquakes, 24, 25
Africa, luck of locality of, 18; granite predominating rock in, 94, 254; explanation of missing lands west of, 279; sliding of, toward Pacific, 316. *See also* South Africa
African Shield, 242, 245, 264, 274
After-shocks of earthquakes, 76–78
Alabama, seismic shocks in, 19; the Appalachians in, 240
Alaska, glaciers of, 34; sea waves of 1899 shock in, 41; coastal uplift of, 64, 66–68, 74; faulting of, 64, 65; asymmetry of mountain ranges of, 235
Aleutian Islands, 218, 235
Allah Bund, the, 64
Alluvium, foundations of, 13, 14, 18
Alpine-Carpathian Mountains, 214
Alpine-Himalayan Mountains, 241, 264; origin of, 317
Alps, the, seismicity of, 6; landslide in, 33; snowslides in, 34; axial trend of, 214; overthrusting of European, 232–235; asymmetry of, 235; reason for height of, 237; effects of erosion on, 238; settling down of rocks of, 318
Altai Mountains, 240
Altaide Mountain Chain, 240
American Mediterranean Rugged Mountain Belt, 218
Americas, the, sliding of, 310, 316, 317
Andalusia, seismic casualties in, 3
Andes, the, submarine slope of, 11; axial trend of, 218; reason for height of, 237
Antarctic Shield, 242, 245, 274
Antarctica, ice-cap of, 179, 201; Andes in West, 218; sliding of, 316
Anticlines, 222, 226–228; eroded, 227
Antillean mountain system, 218, 241, 264, 317
"Antlitz der Erde, Das," by Eduard Suess, 321
Apennines, the, axial trend of, 217
Appalachian Mountains, seismic region of, 20; formation of, 90, 295; geosyncline occupying site of, 203; distribution of, 240; sections eroded and below sea-level, 240; an east-west zone of the earth, 241, 249; fault-blocks of, 259; matching of, with Hercynian Mountains, 284; the revolution of, in Connecticut Valley, 295–299
Appalachian-Hercynian mountain system, formed in Paleozoic Era, 315, 316
Aqueduct, Los Angeles, 42, 43
Arabia, high ground of, 264
Ararat, Mount, 129, 130, 319
Architecture, Byzantine, and seismic damage, 30
Arcs, ground-plans of mountain ranges arranged in, 235–238, 249; garland or festoon form of, 236, 249; of Asiatic mountains, 287; explained by continental migration, 287, 288
Arctic Ocean, possible formation of basin of, 278; absence of mountain chains bordering, 280; relative youth of, 311; origin of, 316
Areal volcanic eruptions, 131
Argentina, 18; seismic casualties, in, 3; basaltic plateau of, 134, 316; mountain system of, 241, 264, 316; ancient glacial deposits of, 285, 286; floor of moving glacier in, 287
Arica, Peru, sea waves of 1868 shock in, 41
Arizona, seismic shocks in, 19, 74; fissure eruption in, 133, 134; uplift of strata of, 237
Arkansas, seismic shocks in, 19; seismic region of northeastern, 20; the Appalachian structure in, 240
Arran, Island of, basalt dike on, 140
Ascension Island, lava flow in, 131; domes of trachytic lava in, 166; analogy of lava flow of, to landslide hypothesis of mountain-building, 272; on Mid-Atlantic Swell, 280
Asia, 10, 310; luck of locality of, 18; energy of landslide in central, 24; mountain trends in, 235–238; the Hercynian chain in, 240; arc form of mountains of, explained by migration of, 287, 288; extent of migration of, 288
Asia Minor, seismogram of 1909 shock in, 87
Asymmetry, of ground-plans of mountain ranges, 235, 249; hemispherical, of earth's interior, 305–310
Atlantic Ocean, disturbances affecting floor of, 16; change in level of, 177, 178; transgression of, upon North America, 201; possible formation of basin of, 278, 279; ridge or swell in middle of basin of, 279–284; type of coast-line of, 279–284,

317; absence of mountain chains bordering, 280; matching of rock structures on two sides of, 284–287; relative youth of, 311; origin of, 316; contrast of coast-line of, with Pacific type, 317
Atlantic Coastal Plain, uplifting of, 90
Atlantis, Plato's legend of the lost, 279
Atlas Mountains, axial trend of, 217
Atolls, the Funafuti and the Suva Diva, 184; Darwin's theory concerning, 185
Aunuu Island, 20-foot emergence of, 175
Australasia, 10; eastward sliding of, 278, 316
Australia, luck of locality of, 18; ancient east-west mountain range in, 241; east-west trend of mountains of, 249; explanation of missing lands between Africa and, 279; floor of moving glacier in, 287; formation of mountains of, 316
Australian Shield, 242–245
Avalanches, 34
Azores, the, on Mid-Atlantic Swell, 280; volcanoes of, 319

Balkan Mountains, 214
Baltic Sea, contemporary rising of northern area of, 187, 196; in Glacial Period, 188–190, 199
Bandai-San, cone of, 158
Banffshire, crumpling of limestone beds in, 224
Barrell, Joseph, his geological history of Connecticut Valley, 293–299; his estimates of duration of geological eras, 314, 315
Basalt, crystallizing of, 95; dominating rock of deep-sea islands, 97, 98; density of crystallized, 97, 99, 101, 278; substratum of non-crystallized, glassy, 100–102, 114, 115, 119, 128, 135, 167, 168; under-layer of earth's crust of, 100, 102, 122, 310; suboceanic, 100, 114, 127; under mountain ranges, 102; white-hot in substratum, 114; densities of crystallized and glassy, 115, 127; lava floods of, 119–121, 133 *ff.*; break between crystallized and non-crystalline not detected, 121; greatest plateaus of, 134; mobility of substratum, 135, 168; vesicular, from Hawaii, 136; erosion of plateaus of, 139–141; of Pacific volcanoes, 143; high fluidity of lava of, 156, 157; lavas other than, 165–167; substratum, heat-bringer in volcanic action, 167; lava flows of, on primitive continent, 316
Basement Complex, 242–249; character of, 248; great age and extent of, 248, 249; universal foundation of North America, 295; intense crumpling of rocks of, explained by crustal sliding, 311; similarity between structure of, and that of ordinary mountain chains, 313; rocks of, crumpled in pre-Paleozoic eras, 315
Basining of earth's crust, under ice-load, 190–192, 197–202; formation of basin, 191; persistence of basin, 197; by weight of lava eruptions, 251–256
Basutoland, lava plateau of, 120, 130
Batholiths, 132
Beaches, raised boulder, 190, 192–198
Bear Island, boulders of, 193
Belgium, 240, 285
Belle Isle, Strait of, crustal uplift at, 194
Belts of seismicity, the two, 6 *ff.*
Benches, wave-cut, rock, 175–178, 190, 196
Bengal, subsidence of coast of, 69
Bone beds of fish carcasses, 40
Bore-holes, temperature measurements at, 111–114
Boston, earthquake of 1755 in, 15; safety of, from seismic damage, 18, 21, 22; built on mountain chain, 239; 200-mile continental shelf off, 284
Boulder-clay, 286
Boulders, left by ice-caps, 192–196
Biwa Lake, Japan, 69
Black Mountain, displacement of, 75
Bradford's "History," earthquake recorded in, 14
Brazil, luck of locality of, 18; basaltic plateau of, 134; an area of prolonged erosion, 242
Brazilian Shield, 242, 245, 264, 274
Britain, in Glacial Period, 189; rock structures of, compared with those of Newfoundland and Nova Scotia, 240, 285; coal-beds of Pennsylvania and of, 285
British Columbia, ice-cap of, 201
Brittany, rock structures of, compared with those of Newfoundland and Nova Scotia, 240, 285
Buildings, effects of earthquakes on, 27; seismic damage lessened by proper construction of, 29, 30, 82
Burnett Creek laccolith, Montana, 162
Bushveld basin, the, South Africa, process of mountain-building in, 252–257; effects of erosion of, 255; size of, 255; sandstone ridges of, 256, 257
Byzantine architecture and seismic damage, 30

Cajon Pass, California, 53
Calabria, seismic destruction in, 2, 3, 25, 41; fissures in, 34; sinking of coast of, 68, 69
Caledonian system of mountain structure, 241
California, seismic casualties in, 1, 3; yearly rate of earthquakes in, 18; number of shocks from 1915 to 1923 in, 19, 20; area disturbed by 1906 quake in, 22; energy of 1906 quake, 23, 24; landslide during 1906 shock in, 30, 33; seismic fountains and craterlets of 1906 quake in, 35, 36; sandstone dikes in, 37, 39; ponds

formed in, during 1906 quake, 39, 40; 1906 earthquake in, caused by San Andreas Fault, 50–61, 65; horizontal displacement of 1906 quake in, 57, 58; earthquakes of 1868 and 1872 in, 62; isoseismal lines of 1906 quake in, 62; the San Jacinto Fault, 74; shock of 1918 in, 74; displacements of triangulation stations of, in 1906, 75; cinder cone near Mono Lake in, 157; sea-cliff near Monterey in, showing buried mountain structure, 292, 293
Callao, Peru, seismic sea waves in, 41
Cambrian Period, North America in, 171, 207
Canada, luck of locality of, 18; earthquakes in, 15, 16; in Silurian period, 207; erosion of northeastern, 208
Canadian Shield, 242, 246, 264, 274
Canyons, 93, 319; cut by Orange River, South Africa, 94; of Colorado River, 237, 245
Cape Cod, crustal uplift of, 201
Cape Fortunas, landslide at, 33
Cape Mugford, Labrador, Basement rocks in cliff at, 246
Cape of Good Hope, 20-foot emergence of, 177
Cape Province, South Africa, bore hole near, 113; upturned sandstone beds in, 221
Carnarvon, South Africa, bore hole near, 113
Carpathian Mountains, axial trend of, 214; asymmetry of, 235
Cascades, lava, in Hawaii, 124
Casualties of earthquakes, table of, 3
Caucasus, the, settling down of rocks of, 318
Caves, sea, indicating sea-level shift, 175–178, 195
Cenozoic Era, duration of, 314; mountain-building of, 317, 318
Central America, seismicity of, 6; east-west Mediterranean Belt in, 248; origin of mountains of, 317; settling down of rocks of, 318
Centrum, seismic, 79
Chamberlin, Professor T. C., tidal-disruption theory of, 104, 300–303
Champlain valley, 201
Charleston, earthquake of 1886 in, 3, 17, 22, 80; shocks from 1915 to 1923 in, 20; craterlets formed during quake in, 36
Chedrang Fault, India, 64
Chief Mountain, Montana, 228–230
Chili, seismicity of, 11; sea wave at Iquique in, 41; areas affected by quakes in, 62
China, records of seismic damage in, 3; damage from landslides in, 33, 34; the Hercynian chain in, 240; settling down of rocks of, 318
Cinder cones, 157
Circle of Fire, the, 318
Circum-Pacific Zone of earthquakes, 6–14
Circum-Pacific Zone of mountains, 218–220, 241, 248, 249, 275, 283, 317; largely submarine, 219, 284; asymmetry of, 235–237; reasons for height of mountains of, 237; origin of, 316; readjustments in, 318; volcanic "Circle of Fire" of, 318
Cistern-rock, 161–165
Cliffs, sea, sedimentary rocks in, 96; of basaltic lava, 120; exposing ancient mountain structure, 246, 292, 293
Coast, sea, uplifting of, 66–68, 72; subsidence of, 68, 69
Coast-line, contrast between Atlantic and Pacific types of, 317
Colima volcano, 318
Colorado, seismic shocks in, 19
Colorado River, Grand Canyon of, 237, 245
Columbia River Valley, in Glacial Period, 180
Compression, of ground and seismic waves, 28, 29; sound waves of, 83, 84; increase in earth's internal density accounted for by, 104–106; of interior of earth, 126; horizontal, of earth's crust in mountain-building, 222 ff., 249, 251, 260 ff.
Condensational sound waves, 83–85
Cones, volcanic, formation of, 141, 142, 148; effect of explosions on, 157, 158; cinder, 157; erosion of, 159; instability of, 167, 168
Connecticut Valley, fault-block mountains of, 256, 259; geological history of, 293–299; the Appalachian revolution in, 295–299; in Glacial Period, 299
Constant, the precessional, 104
Constantinople, 6
Continent, theory of a single, primitive, 310–314; doming and furrowing of primitive, 242, 264, 267, 274, 275, 315, 316; crustal tension of primitive, 316, 317; sliding toward Pacific and breaking of single, into huge fragments, 316
Continents, flotation of, 91, 92, 99, 126, 170, 311; dominant rocks of, 95–98; density of, 99, 100; isostasy or balance of, 99; basaltic rock under, 100; two layers of crust of, 122; average height of, 170; warping of, 171, 174 *ff.*, 209, 210; theory of migration of, 260 *ff.*, 305; hypothesis suggesting reason for migration of, 263 *ff.*; tests of sliding hypothesis of mountain-building, 275–289; extent of migration of, 278, 279, 291; missing lands accounted for by theory of migration of, 279; arc form of high mountains and migration of, 287, 288; crustal depressions in front of sliding, 289; separation of, from ocean, 305–312; outlines of present, at 100-fathom line in sea, 312
Contraction, earth distorted because of interior, 265–274; energy of position of crust through, 271

Convection currents, in formation of primitive continent, 313, 314
Coral reefs, growth of, in post-Glacial time, 184; Darwin's theory concerning, 185
Cordillera, the, 284; distribution of, 90; chronic seismicity of, 21; in Mississippian Period, 171; geosyncline of, 204; submarine trend of, 218; uplift of region of, 237; fault-block mountains of, 259
Core, earth's, composition of, 107, 108, 126; density of, 107, 109
Cornwall, 240
Cosmogony, theories of, 110
Crater Lake, Oregon, sinking of volcanic cone in, 168
Craterlets, seismic, 35–39
Craters, volcanic pit, 151; Halemaumau crater, 151–156
Cretaceous Period, North America in, 171; Europe in, 208; Connecticut in, 296, 297
Crust, earth's, relief of elastic strain in, cause of earthquakes, 47 *ff.*; deleveling of, 65 *ff.*, 174 *ff.*, 186 *ff.*, 209, 210, 305 *ff.*; thickness of, 81, 91, 111, 119, 211; three classes of rocks in, 91; the skin of the earth, 100; distribution of densities in, and below, 100, 101; average density of, 103; character of, 107, 110 *ff.*, 211; density of, contrasted with density of substratum, 110 *ff.*, 135, 270; physically distinct from glassy substratum, 110 *ff.*; sinking of blocks of, into substratum, 110, 269 *ff.*, 276, 277; theory of formation of, 110, 111; cause of instability of, 110 *ff.*; rise in temperature of, with increase of depth, 111–114; isostasy of, 114; separation of, into two layers, 122, 123, 310; means of measuring thickness of upper layer of, 122, 123; pressure at bottom of, cause of fissure-eruptions, 135; not endangered by fissure-eruptions, 138; basining of, under glacial load, 190–192, 197–202; uplift of, indicated by boulder beaches, 193–198; mechanism of uplift of, 196–202; down-warping of, by geosynclinal prisms, 203–206; weakest part of, located at geosyncline, 206, 268; a mass of crystals, 211; mobility of earth shown through warping of, 212; warping of, into polar domes and equatorial dome-arch, 242, 264, 265; horizontal compression of, 249, 251, 260 *ff.*; basining of, through lava weight, 251–256; reasons for distortion of, 265 *ff.*; a poor conductor of heat, 265, 266; temperature of, 266; leakage of heat through, 266; infall of, 266 *ff.*; mountain structures formed by sliding of blocks of, 269 *ff.*; energy of position of, effect of interior contraction, 271; analogies illustrating landslide hypothesis of mountain-building, 271–273; diminished rotation a cause of down-warping of, 273; deleveling and sinking of, the two conditions for mountain-building, 289; trough-like depressions of, in front of mountain arcs, 289; formation of, through heat radiation, 303, 304, 309, 310; higher in one hemisphere than in other, 310; concentration of whole of granitic, in one hemisphere, 310–312; deformation of, in Basement Complex, 315; readjustments of, 317–320
Crystal Springs Lake, California, 58
Crystallizing of granite and basalt rocks, 95
Crystals, earth's crust a mass of, 211
Curtis, George C., model of Kilauea sink by, 150

Darwin, Charles, his theory of coral reefs, 185
Darwin, George H., his theory of moon's origin, 307–309
Day, the, lengthening of, 273
Deccan basalt plateau, India, 134
Deleveling, of earth's crust, 50 *ff.*; 65 *ff.*, 174 *ff.*, 186 *ff.*, 209, 210, 305 *ff.*
Denmark, Southern, contemporary warping of, 187; super-elevation and lowering of, 199, 200
Density, of earth's interior, and stability of earth, 92; of underground rocks, 94; of salt and fresh water, 98; of rocks beneath ocean and continents, 99; distribution of, in earth's crust and below, 100; table of, 101; facts indicating increase of earth's internal, with increase of depth, 102 *ff.*, 307; table of, at different levels in the earth, 109; contrast of, in crust and substratum, 110, 135, 289; of crystallized and glassy basalt, 115
Dikes, sand, 35–39; sandstone, 37, 39; of solidified lava, 140, 141, 278; multiple, 140; volume and dimensions of lava, 144; gas-fluxing in lava of, 144–147
Dinaride mountain group, 217
Dinosaurs, 311
Discontinuity in European rocks demonstrated by seismograms, 123
Disenchantment Bay, Alaska, crustal uplift around, 67
Displacement, horizontal, of California quake of 1906, 57; of Japanese quake of 1891, 58, 64; vertical along San Andreas Rift, 58; measurements of horizontal, 62–66; of sea bottom, 70–73; of rocks, causing earthquakes, 74; of triangulation stations, 75, 76
District of Columbia, seismic shocks in, 19
Doming of earth's crust, 263 *ff.*; of primitive continental lands, through cooling contraction, 274; of primitive continent as a whole, 316
Down-sliding hypothesis of mountain-building, 263 *ff.*; 310–314

Down-warping, major zones of, 243
Dry land, existence of, explained by continental migration theory, 311–314

Earth, low pitch of sounds of, 82; discovery of nature of interior of, 82; interior of, and study of seismic motion, 89; importance of study of interior of, 91 *ff.*; crust of, 91; stability of, dependent upon densities of interior, 92; the substratum of, 100 *ff.*; facts indicating increase of internal density of, with increase of depth, 102 *ff.*; ellipticity of, 103, 306; not homogeneous, but composed of shells, 104; compressibility of, 104–106, 124, 206; precessional constant and moment of inertia of, 104, 105; tidal-disruption theory of origin of, 104, 300–303; composition and depth of concentric divisions of, 107, 108; composition of core of, 107, 108; densities at different levels in, 107–109; layers of, stratified by density, 109; facts indicating non-crystalline, glassy substratum below thin crust of, 110 *ff.*; theory of hot liquid condition of, 110; theory of formation of crust of, 110, 111; evidence supporting hypothesis of crust and substratum, 110–119; rigidity of, 124, 211; the invisible, the real, 125; contradiction in rigidity and liquidity of, 128 *ff.*; deleveling of crust of, 174 *ff.*, 186 *ff.*, 209, 210, 305 *ff.*; mobility of, shown in earthquakes and in volcanoes, 211; mobility of, shown in warping, 212; mobility of, shown in mountain-building, 212 *ff.*, 320; mid-latitude furrowing of surface of, 264, 265, 274; doming of continental part of crust of, 263 *ff.*, 274, 316; contour of, before mountain-building, 264, 274; reasons for distortion of crust of, 265 *ff.*; diminishing rate of rotation of, 265, 273, 274; contraction of interior of, 265 *ff.*; nearly constant surface temperature of, 266; cooling of interior of, through leakage of heat, 266; infall of crust of, 266 *ff.*; protean character of, 292; reading of history of, from rocks, 292–299; two tidal cones in, 300, 301; stages in evolution of, 303–306; gaseous state of, 304, 306; fluid stage of, 304, 306; internal asymmetry of, 305–310; division of, into land and water hemispheres, 305–312; viscosity of interior of, 306, 307; theories of moon as originally part of, 307–309; crusting of, through heat radiation, 309, 310; sketch of history of development of, 315–320; face of, still changing, 320
Earthquake Investigating Committee, State, 50
Earthquakes, of Japan, 1, 10, 11; at Lisbon and Messina, 2; early records of, 3, 13; table of casualties of, 3; in China, 3; two zones of, 6–14, 318; of the Tuscarora Deep, 10; of the Tonga Plateau, 10; recording of, by seismographs, 13, 14, 86–88; no part of earth indefinitely free from, 14; centers of, in crust under western Pacific, 18; number of, in United States from 1915 to 1923, 19; the Rossi-Forel scale of intensities of, 21; causes of, 21, 22, 45 *ff.*, 116; table of areas sensibly shaken by, 22; amount of energy of, 22, 23; volcanic, 23, 46, 88; kinds of motion of, 24–29; reasons for destructive effects of, 24 *ff.*; accelerations of particles in, 25; monuments displaced by, 25, 26; table of to-and-fro motion during, 27; destruction of buildings in, 27; ground waves of, 27–29; building construction and, 29, 30; engulfment in fissures of, 34–39; avalanches caused by, 34; fountains, craterlets, and sand dikes of, 35–39; ancient, located through exposure of sandstone dikes, 39; effects of, on springs and rivers, 39, 40; sea waves due to, 40, 41; ponds formed by, 40; fire caused by, 41–43; water-supply systems destroyed by, 41–43; science and, 44; series of vibrations through earth's crust, 45; fault or tectonic, 47 *ff.*, 88; elastic-rebound theory of, 47 *ff.*, 116; tests of elastic-rebound theory of, 74–81; explanation of Californian of 1906, 50–62; deleveling caused by, 65 *ff.*, 187; after-shocks of, 76–78; relation between volcanoes and, 78, 79; the epicenter of, 79, 80; focus of, 79–83; possibility of forecasting place and time of, 81; earth's interior and study of motion of, 82, 89; the sounds of, 82 *ff.*; "earth dyne," Anglo-Saxon name for, 82; condensational or longitudinal and transverse sound waves, 83–85; P, S, and M waves of motion of, 87, 88; refraction and reflection of wave-paths of, 88; value of discovery of cause of, 89; velocity of wave propagation of, 105, 109, 122; depth of origin of, 116, 119; mobility of earth shown in, 211; accompanying crustal readjustments, 318
East Indies, seismicity of, 6; volcanic explosion in, 46; emerged tops of mountains, 238; formation of mountains of, 284
East-West Mid-Latitude Zones of mountain chains. *See* Mediterranean Zone of mountains
Eastport, Maine, shock at, 16
Effervescence of volcanic magma, 136, 137, 145, 168
Elastic-rebound theory of earthquakes, 47 *ff.*, 116; and changes of level, 65 *ff.*; tests of, 74–81
Elburz, 319
Ellipticity of the earth, 103, 306
Energy, seismic, 22, 46, 65; table of seismic, 23; of landslides, 24

Engineering, practical application of seismology to, 82
England, rock structures of, 240, 285; old red sandstone of, 285
Enoshima, Japan, seismic uplift at, 72
Eocene Period, coast-line of North America in, 171
Epicenters of earthquakes, 79, 80; the sounds near, 82
Equator, belt of high ground along, 103, 242, 250, 264; lessening of bulge at, 273; sliding together of dome of, and North Pole dome, 315
Equinoxes, precession of, 103, 104
"Erdbebenkunde," by A. Sieberg, 321
Erosion, stratified rock formed by, 114; of Basutoland plateau, 131; of plateau basalts, 139–141; of volcanic cones, 159; surface loading, due to, 202–208; of folded rocks, 222, 227; of Pennsylvania mountains, 228; of anticlines and synclines, 227; ruggedness of mountains caused by, 238, 239, 291; mountains destroyed by, 239; the chief areas of prolonged, 242, 274; rough relief of Basement Complex wiped out by, 248; marine, on rock strata, 251; of the Bushveld basin, South Africa, 255; of fault-block mountains, 259; distortion of earth caused by, 265; of Appalachian mountains of Connecticut Valley, 295, 297, 299
Etna, Mount, 319; fissure eruptions on, 141; long-lived activity of, 144
Eurasia, plateau of, 91; Mediterranean Rugged Mountain Belt of, 217 *ff.*, 235, 248, 264; the Hercynian chain traversing, 240, 241; supposed eastward sliding of, 278, 316, 317
Europe, luck of locality of northern, 18; thermal gradients in borings in, 112; in Cretaceous Period, 208; axial trend of mountains of, 214; possible eastward sliding of, and separation from North America, 279–284; explanation of missing lands west of, 279
Everest, Mount, 219
Experiments, imitating rock folds and thrusts, 224–226, 238
Explosions, volcanic, 46, 153–156; a subordinate element of volcano, 156, 157; effect of, on volcanic cones, 157, 158

Farallon Lighthouse, displacement of, 75
Fault-block mountains, 256–260, 297
Fault planes, 48 *ff.*
Fault scarps, 48 *ff.*; measurements of, 62–66; of San Andreas Rift, 50–54, 74; in Owens Valley, 62, 63; changes of level proved by, 65 *ff.*; ancient, 74; the San Jacinto, 74
Faulting, earthquakes caused by, 47 *ff.*, 58 *ff.*, 65, 74, 76, 79, 88; in San Andreas Valley, 50–54, 74; in Japanese earthquake of 1891, 58; in Owens Valley, 62, 63; of ancient earthquakes, 74; rock character determined through natural sections caused by, 94; mountain-building through, 256–260, 297; accompanying crustal readjustments, 318
Fence, offset in, caused by faulting, 57, 58
Ferrospars, 106, 107
Fiji Islands, 10
Finch, R. H., earthquake statistics of, 19; quoted, 20
Finland, in Glacial Period, 188–190; submergence of, 190; shield rocks of, 245
Fire caused by earthquakes, 41–43
Fish, killed by earthquakes, 15, 40
Fissures, engulfment in earthquake, 34–39; gases from, 40; primary and secondary, 65; escape of substratum through, 124; lava eruptions through, 130–141, 318; cause of eruptions through, 134 *ff.*; abyssal, 134 *ff.*, 160 *ff.*, 277, 278; effervescence of lava through, 136, 137; retarding of lava outflow from, 137; earth's crust not endangered by eruptions from, 138; lava dikes filling ancient, 140, 141; central type volcanoes due to abyssal, 141–143; dimensions of abyssal, 144; subordinate and principal volcanoes from abyssal, 163; vents fed directly from abyssal, and those not fed directly from, 163; from crustal tension of primitive continent, 316
Fissuring, vibration due to, 46; theory of abyssal, 134 *ff.*, 160 *ff.*, 277, 278
Flagstones, layers of, 221
Florence, seismic disturbances in, 13
Flotation, of continents, 91, 92, 99, 170, 311; mountains and plateaus supported by, 91, 102
Focus, seismic, 79; depth of, 80, 81; and wave paths, 83; and P and S waves, 88; shallowness of, 116
Folding, mountain height attained long after, 115, 275–277, 289–291, 319
Folds, rock, in mountain-building, 222–235; experiments imitating, 224–226, 238
Force, seismic, estimated by acceleration, 24
Forecasting place and time of earthquakes, 81
Foredeeps facing mountain arcs, 289
Formosa, faulting and displacement in, 64, 65
Fossils, 39; ages of rocks determined through, 314
Foundations, city, and seismic damage, 13, 14, 18
Fountains, seismic, 35–39; lava, 153–155
Fracturing of earth's crust. *See* Faulting
Frech, geologist, 30
Fujiyama, supposed origin of, 69; the cone of, 148

Funafuti atoll, model of, in Harvard Museum, 184
Furrows, earth's two mid-latitude, 264, 265, 274; continental sliding toward, 275

Galitzin, Prince, seismogram of, 87
Garo Hills, changes of level in, 66
Gas, from seismic fissures, 40; of volcanic lava, 129, 136, 137; fluxing of volcanic, 144–147, 151, 155, 156, 160, 162, 168; rhythmic movement of volcanic, 147; extinction of volcano due to lack of, in magma chamber, 148; chemical reaction of, cause of volcanic heat, 153; not all volcanic explosions due to magmatic, 158; the earth a mass of hot, 304, 306
Geological time, changes in North America in, 171–173, 207, 208; duration of chief eras of, 314, 315
Geology, importance of study of, 44; most important book on, 321; text-books of, 322
Geophysical Laboratory at Washington, 153
Georgia, seismic shocks in, 19
Geosynclinal prisms, mountain-building through prolonged sedimentation of, 203–205, 220, 226, 239, 242, 260; the major east-west, 203, 242, 250, 264, 265, 274; Basement Complex beneath, 245–248; theory of horizontal crushing of, through continental migration, 260–271; sliding and crumpling of east-west, 315, 316; thickening of, along primitive Pacific shores, 316
Geosyncline of Punjab, 289
Germany, volcanic vents of laccolith in, 163; Baltic coast of, 187; northern, in Glacial Period, 189, 199; crustal lowering of northern, 200; the Hercynian chain in, 240
Geysers, seismic effects on, 40; of Yellowstone National Park, 132, 133
Gibraltar, Strait of, sinking land of, 279
Glacial Period, principal ice-caps of, 180–183; sinking of sea-level during, 180; last European ice-cap of, 188–191; basining of earth's crust under ice-load in, 190–192, 197–202; last North American, 191–194, 209, 286; Connecticut in, 298, 299
Glaciers, Alaskan, 34; formation of, 179; increase of, cause of lower sea-level, 179, 209; the Labrador, Keewatin, and Cordilleran, 180; effect of, on mountains, 238; deposits made by, in Paleozoic Era, 286; striated rock floors of moving, 287; origin of, in upheavals to great height, 319; mountain sculpturing due to eroding, 320
Glass, in formation of igneous rocks, 95; of substratum, 92, 108, 114–116; lessening of rigidity of substratum, 124; conversion of foundered crustal blocks into, 277
Globe, the, history of, from completion of single, primitive continent, 315–320
Gneiss, banded, 97; rate of increase of temperature in, 113; formation of, 247
Gorges, formed by mountain torrents, 319
Gould, Mount, Montana, 161
Grand Canyon of the Colorado, 237, 245
Granite, principal continental rock, 94–97, 122; crystallizing of, 95; metamorphism of, 96, 97; density of continental, 99; radioactivity of, 101; of mountain ranges, 102; density of, at zero pressure, 106; rate of increase of temperature in, 113; upper layer of earth's crust composed of, 122; lavas of, 165, 168; chief constitutent of Basement Complex, 246, 247; crust rocks of Africa of, 254; land hemisphere differentiated from water hemisphere through concentration of light rocks of, 305 *ff.*, 311–314; formation of crustal layer of, 310
Gravity, 315; and acceleration of earthquakes, 25; strain on earth's crust through force of, 47; continental, and the sea-level, 99; earth's ellipticity partly due to, 103; continental migration through, 263
Great Britain, in Glacial Period, 189; rock structures of, compared with those of Newfoundland and Nova Scotia, 240, 285; coal-beds of Pennsylvania and of, 285
Great Lakes, tilting of region of, 187
Great Plains of America, 229, 230, 277
Greenland, ice-cap on, 201; erosion of, 208; shield rock of, 242; basaltic lava floods in, 316
Guatemala, seismic belt through, 54
Gulf of Finland, rise of ground opposite, 187; boulder beach on island in, 195
Gulf of Mexico, coast-line of, in Eocene Period, 171
Gutenberg, seismologist, 122

Halemaumau, model of, in Harvard Museum, 150; lava lake in crater of, 151–154, 164; dormancy of, 155; explosions at, 155; facts indicating laccolith under, 163–165
Harvard University Museum, model of Kilauea sink in, 150; model of Funafuti atoll in, 184
Harz Mountains, 240
Hawaii, world's greatest volcano, 91; basaltic flow in Kilauea Sink, 98; lava lake of Kilauea, 120, 121, 151–156, 164; lava cascades in, 124; a vesicular basalt from, 136; alignment of volcanoes of, 143; model of Kilauea Sink, in Harvard Museum, 150; lava lake of Mauna Loa, 155, 164; volcanic neck in island of Maui, 159; facts indicating laccolith in, 163–165; analogy of lava lake of Kilauea in, to landslide hypothesis of mountain-building, 271
Hawaiian Volcano Research Association, 19

Haywards Fault, 62
Heat, volcanic activity and, 147; origin of volcanic, 153; leakage of, through earth's crust, 266, 309, 310
Heavens, Mount, Montana, 223
Height, mountain, attainment of, after folding, 115, 275–277, 289, 319; explained by continental sliding theory, 290, 291
Heiskanen, W., 306, 309
Helmert, 306, 309
Hemispheres, separation of land and water, 305–312; concentration of whole of granitic crust in one, 310–313
Henry Mountains, 251
Hercynian Mountain System, 240, 241, 249; matching of, with Appalachians, 284; formation of, in Paleozoic era, 315, 316
Hercynian-Appalachian Mountain System, 283
Hereford, spread of sound during earthquake at, 83
Highwood Mountain, 251
Himalaya Mountains, 241; seismic belt of, 6; axial trend of, 217; asymmetry of, 235; garland form of, 237; reason for height of, 237; arc forms of, explained by continental migration, 287, 288; the foredeep facing arc of, 289; origin of, 317
Hogland, Island of, boulder beach on, 196
Horizontal compression, 222 *ff.*, 249, 251, 260 *ff.*
Horizontal displacement, 57, 58, 62–66, 74–76
Hudson Bay, crustal uplift at, 194
Hudson valley, 201
Humboldt County, California, landslide in, 30; seismic belt through, 54
Huron, Lake, tilting of region of, 187
Hypocentrum, seismic, 79

Ice-caps, formation of, 179; increase of, cause of lower sea-level, 179 *ff.*; of Glacial Period, 180 *ff.*; maximum thicknesses of, 180; last European, 188 *ff.*; the Scandinavian, 188–191; the Labrador, 191–194; boulders left by, 192–196; crustal uplift through melting of, 197–202; distortion of earth under load of, 209; hypothesis of tearing apart of continental, 287; of Connecticut Valley, 299
Iceland, landslides in, 33; earthquake fissures in, 34; geyser formed in 1896 shock in, 40; fissure eruptions in, 133; the Laki fissure of, 142; basaltic lava floods in, 316
Idaho, seismic shocks in, 19; basaltic plateau in, 134
Iddings, J. P., "Igneous Rocks," by, 321
Igneous rocks, 94–97; crystallizing of, 95; origin of, 129
"Igneous Rocks," by J. P. Iddings, 321
Illinois, earthquake shocks in, 19; active seismic region in southern, 20
India, seismic casualties in, 3; area disturbed by 1897 and 1907 quakes in, 22; acceleration of quakes in, 25; torsion of a monument and of ground in, 26; to-and-fro motion of 1897 quake in, 27; landslides of 1897 quake in, 30; deleveling in, 40, 66; fish killed by quake in, 40; energy of 1897 quake in, 47; faulting and displacement, 64, 65, 76; Deccan basalt plateau of, 134; basaltic lava floods in, 316; settling down of rocks of, 318
Indian Ocean, the Suva Diva atoll in, 184; possible manner of formation of basin of, 278, 279; absence of mountain chains bordering, 280; relative youth of, 311; origin of, 316
Indian Shield, 242, 245, 264, 274
Indiana, seismic shocks in, 19
Indus River, quake of 1819 near, 64
Inertia, earth's moment of, 104, 105
Intensity, seismic, 22; table of, 23; of California quake of 1906, 62
Iowa, shocks in, 19
Iquiqui, Chili, sea waves of 1877 shock in, 41
Iranide Mountains, axial trend of, 217
Iron, metallic, of meteorites, 106, 107; core of, at earth's center, 107, 108, 126; between outer shell and core of earth, 108
Isacoustics, 83
Ischia, volcanic quake of 1883 in, 22, 23, 46
Islands, deep-sea, formed of basalt, 97, 98
Isobaths, 10
Isoseismal lines, 79, 80; of Charleston earthquake, 16; of California earthquake of 1906, 59–62
Isostasy, of continents, 99; character of crust and substratum indicated through, 114–116
Italy, seismic destruction in, 2, 3; seismic areas in, 13; number of shocks per year in, 14; avalanches caused by 1915 quake in, 34; migration of earthquake centers in, 77; explosion crater of Lake Nemi in, 158

Jagger, Dr. T. A., 150; rock-thrust experiment of, 226
Jamaica, seismic casualties in, 3
Japan, earthquake of 1923 in, 1, 13, 14; seismic casualties in, 3; the Tuscarora Deep off, 10; origin of earthquakes of, 10, 11; seismicity of, 11; early seismic records of, 13; number of earthquakes in, recorded by seismograph, 13; density of population in, 18; area shaken by 1891 quake in, 22; energy of 1891 quake, 23; acceleration of 1891 quake, 25; to-and-fro motion of 1891 and 1894 quakes in, 27; compression of ground in 1891 quake in, 28; use of roof tiles in, 29; landslides of 1891 quake in, 33; earthquake fissures in, 34, 35; damage to canals in, 35; sea waves of various shocks in, 41; fault scarps formed during 1891 quake in, 48,

49; horizontal displacement in, 58, 64; fault causing 1891 quake in, 64, 65; seismic deleveling in, 68–73; soundings of Sagami Bay made by, 71; after-shocks of 1923 quake in, 76; principal volcanoes of, 79; cone of Fujiyama, 148; explosion of Bandai-San in, 158; warping of harbors of, 187; emerged tops of mountain chains, 237
Japanese Hydrographic Office, 70
Java, volcanic cones of, 142
Jeans, J. H., tidal-disruption theory of, 104, 301–303
Jeffreys, H., tidal-disruption theory of, 104; his theory of the evolution of the earth, 303
Judith Mountain, 251
Jura, Island of, raised beaches of, 198, 199
Jura Mountains, axial trend of, 214; examples of folded mountains, 228
Jurassic Period, Connecticut in, 296, 297

Kamakura, earthquake of 1923 in, 14
Kansas, seismic shocks in, 19
Kansu, seismic casualties in, 3; landslide in, 33
Kant, nebular hypothesis of, 300, 304
Kasbek, 319
Kentucky, earthquake shocks in, 19; seismic region of western, 20
Kermadec Deep, 10
Kilauea Sink, Hawaii, basaltic flow in, 98; lava lake of, 120, 121, 151–156, 164, 271; model of, in Harvard Museum, 150; "Old Faithful" in, 153; fountains of molten rock in, 153, 154; phreatic explosion at, 158; facts indicating laccolith under, 164, 165; analogy of lava lake of, to landslide hypothesis of mountain-building, 271
Kimberley, South Africa, glacially striated rock pavement near, 287
Kingston, Jamaica, weakness of foundation of, 18; 1692 earthquake at, 40
Knott, his theory of P and S waves, 88
Krakatoa, volcanic explosion of 1883 on, 46, 142
Kurile Islands, 218

Labrador, dry land since Mississippian Period, 171; crustal warping after melting of ice-cap of, 191–194, 201; boulders left by ice-cap of, 192–195; Basement Complex in, 246; rocks of Scottish Highlands and, 285
Laccolith, 251; in Montana, 161, 162; in Swabia, Germany, 163; facts indicating a Kilauean, 163–165
Lake, lava, at Kilauea, 151–156, 164, 271; lava, of Mauna Loa, 155, 164
Laki fissure, Iceland, volcanic cones of, 142
Land, average height of, 170; missing, east of North America and west of Europe, 279; separation of hemisphere of, from water hemisphere, 305–312; one hemisphere of, 310. *See also* Continents
Landslide hypothesis of mountain-building, 263 *ff.*; and single primitive continent, 310–314
Landslides, energy of, 24; damage from, 30, 33, 34; changes in river drainage caused by, 40; in mountainous regions, 46; from faulting in San Andreas Valley, 54
Laplace, mathematical law framed by, 105; nebular hypothesis of, 300, 304
Lava, crystallizing of, 95; predominance of basalt in, 100; basaltic flows of, 119–121, 133 *ff.*, 278; cascades of, in Hawaii, 124; liquidity of earth's interior evidenced by, 128; temperature of, 129, 147; composition of, 129; plateaus of, 130–132; rhyolite, 132; density of substratum, 135; effervescence of, 136, 137; retarding of outflow of, at earth's surface, 137, 138; chambers of, in earth's crust, 144–147; lake of, at Kilauea, 151–156, 164, 271; fountains of, at Kilauea, 153, 154; at Mauna Loa, 155, 164; exploding, 153–156; high fluidity of flows of, 156, 157; volcanic neck of, 159; sills of, 160; laccoliths formed by, 161–165, 251; chemical diversities of, 165–168; origin of non-basaltic, 165; trachytic, 166, 167; basining of earth's crust under weight of, 251–256; analogy of flows of, to landslide hypothesis of mountain-building, 271–273; solidification of flow of, 272; during Appalachian revolution, 297; floods of, on primitive continent, forming ocean basins, 316
Leland Stanford University, memorial arch at, 27
Leonardo da Vinci, 219
Life, dependence of, on delicate physical adjustments, 170
Lima, Peru, sea waves of 1724 shock in, 41
Lisbon earthquake of 1755, casualties of, 2, 3, 15; energy of, 23; landslides of, 33; sea waves of, 41; beliefs concerning, 45
Lithospors, 106, 107
Locality, the luck of, 5, 13, 18
Loma Prieta, displacement of, 75
London, luck of locality of, 6
Los Angeles aqueduct, 42, 43, 63
Luing, Island of, Scotland, rock bench on, 197

Madeira, volcanoes of, 319
Magma, 129. *See* Lava
Maine, 1904 quake in, 15, 16, 22; seismic shocks in, 19
Malaria, from swamps, 40
Mallet, seismic losses estimated by, 4; and seismic focus, 80, 81

Margerie, Emm. de, his translation of "Das Antlitz der Erde," 321
Maryland, seismic shocks in, 19
Masonry, use of rubble, in Messina, 30
Massachusetts, early earthquake shocks in, 15; number of shocks from 1915 to 1923 in, 19; earthquake of 1755 in, 21; 200-mile continental shelf off, 284
Maui, Island of, Hawaii, volcanic neck in, 159
Mauna Loa, fountains on lava lake of, 155; suggested connection of, with Kilauea, 163–165
Mayon volcano, 130
Mediterranean Rugged Belt of Eurasia, 217 *ff.*, 248
Mediterranean seas, seismic belt of, 6
Mediterranean Zone of mountains, 6–14, 235, 237, 241, 264, 275, 283; distribution of, 217 *ff.*, 248, 249; relation of, to Hercynian chain, 240; readjustments in, 318; volcanoes of, 318, 319
Memorial Arch, Leland Stanford, 27
Mendoza, Argentina, 18
Mesozoic Era, 316; duration of, 314
Messina earthquake of 1908, casualties of, 2, 3; areas shaken by, 22; acceleration of, 25; flexure of pavement by, 28, 29; sea waves of, 41; regional subsidence of, 68, 69; effect of city's weak foundations in, 18; destruction of, due to rubble masonry, 30
Metamorphic rocks, 96, 97
Meteorites, composition of, 106, 107; chemical samples of earth material, 107, 108
Mexico, landslides in, 33; sea waves of 1909 shock in, 41; seismic belt through, 54; fault scarps in, 63–65; volcanoes of, 318
Michigan, seismic shocks in, 19
Michigan, Lake, tilting of region of, 187
Mid-Atlantic Swell, 279–284
Mid-latitude furrows, earth's two, 264, 265, 274
Migration of continents, theory of, 260 *ff.*, 310 *ff.*; hypothesis suggesting reason for, 263 *ff.*
Milne, John, 40, 88
Minerals, radioactivity of, 315
Minnesota, seismic shocks in, 19
Mississippi Valley, number of shocks from 1915 to 1923 in, 19; area shaken by 1811 quake in, 22; energy of 1811 quake, 23; landslides in, 33; earthquake fissures in, 34; sand dikes in, 36; subsidence of 1811–1812 in, 69
Mississippian Period, North America in, 171, 207
Missouri, earthquake shocks in, 19; seismic region of southeastern, 20
Mohave Desert, 1922 shock in, 43; fault scarp in, 57
Mokuaweoweo, lava lake of, 164
Mono Lake, 259
Monolith on Saint Helena Island, 159
Montana, seismic shocks in, 19; laccoliths in, 161, 162, 251; overthrust of Chief Mountain in, 228–230
Monterey, California, sea cliff near, showing buried mountains, 292, 293
Monuments, displaced by earthquakes, 26
Moon, effect on, of earth's moment of inertia, 104; tidal attraction of, 300, 301; theories of origin of, 306–310, 313
Motion, seismic, kinds of, 24–29; measurement of amounts of actual, 26, 27; table of to-and-fro, 27; horizontal, 57, 58; character of, 82 *ff.*; discovery of nature of earth's interior through study of, 82, 89; method of recording, 86–89
Mound of God, 64
Mount Holyoke ridge, 297
Mountains, and seismicity, 9–12; supported by flotation, 91, 102; character of rocks forming, 102; and contrast in crust and substratum density, 110; due to mobility of glassy substratum, 115, 116, 125; attainment of height in, 115, 237–239, 289–291, 319; horizontal compression of earth's crust essential element in formation of, 174, 206, 249; formation of, at geosynclines, 206, 220 *ff.*; proof of earth's mobility, 212 *ff.*, 320; confined to belts or zones, 212, 219, 241; below sea-level, 218 *ff.*, 237–240, 275; the Mediterranean Rugged Belt of Eurasia, 217 *ff.*; the Circum-Pacific Belt of, 218–220, 241, 248; American Mediterranean Rugged Belt of, 218; rock folds and thrusts in building of, 222–235; experiments imitating folds in, 224–226; asymmetry of, 235–238, 249; arcs formed by ground-plans of, 235–238, 249; garland or festoon form of, 236, 237; effect of glaciers on, 238; effects of erosion on, 238, 239; four stages of formation of rugged, 239; antiquity of, 239; east-west mid-latitude zones of, 241, 248; chiefly built from stable areas of continents, 242; the Basement Complex the oldest, 248; reason for great height in, 249, 275–277; structure, the essence of, 251 *ff.*; formation of laccolithic, 251; formation of, through basining of earth's crust under lava weight, 252–257; building of, by crustal faulting, 256, 259; origin of force responsible for, 259 *ff.*; landslide hypothesis explanation of, 260 *ff.*; analogies illustrating crust-sliding explanation of, 271–273; tests of sliding hypothesis of building of, 275–289; of Atlantic and Pacific types of coast-line, 284, 317; arcurate forms of high, explained by continental migration, 287, 288; foredeeps facing arcs of, 289; two conditions for building of, 289; buried ranges of, 292–299; development of fault-block, 297; products of sliding con-

tinental blocks, 305; suggested origin of, in convective movements in earth's interior, 313; significance of circum-Pacific belt of, 317; building of existing Alpine type, 317; building of, during Cenozoic Era, 317, 318; building of, along Mediterranean Zone, 318, 319; marvelous sculpturing of, through eroding glaciers, 320

Naples, earthquake of 1857 in, 3, 22; outside seismic zone, 13
Napoleon, 159
Nebraska, seismic shocks in, 19
Neck, volcanic, formation of, 159
Nemi, Lake, Italy, explosion crater of, 158
Neo Valley Rift, Japan, displacement at, 58
Neolithic Period, increase of ice-caps in late, 170
Nevada, seismic shocks in, 19; strongest earthquake in, during nine-year period, 20; faulting in, 49, 63, 65, 74
New Brunswick, earthquake in, 16
Newbury, records of earthquakes in, 15
New England, records of earthquakes in, 14–16; freedom of, from earthquakes, 21; effects of post-Glacial period on, 201; glacial till of, 286; geological evolution of, 293–299
Newfoundland, post-Glacial warping of, 193–195; the Appalachians in, 240; mountains of, compared with those of Britain and Brittany, 284, 285
New Guinea, subsidence of 1907 quake in, 69
New Hampshire, seismic shocks in, 19
New Jersey, seismic shocks in, 19
New Madrid, 1811–1812 quakes of, 33
New Mexico, seismic shocks in, 19
New York City, improbability of seismic damage to, 19, 21, 22
New York State, number of shocks from 1915 to 1923 in, 19; freedom of, from earthquakes, 21
New Zealand, faulting of 1848 and 1855 in, 64, 65; regional uplifts in, 68
Noises, earthquake, 82 *ff.*
Norris Geyser Basin, 132
North America, changes in physical geography of, in early geological periods, 171, 207; composite ice-cap of, at maximum of glaciation, 180; effects of melting of ice-cap of, 201; geosynclines of, 203; warping of, 206–208; Basement Complex exposed in, 246, 247; theory of westerly sliding of, 260 *ff.*, 278–284, 310, 316, 317; explanation of missing lands east of, 279; formerly joined to Europe, 279–284
North Carolina, seismic shocks in, 19
North Dakota, seismic shocks in, 19
North Pole, dome of high ground around, 250, 264; sliding together of dome of, and Equatorial dome, 315
North Sea, lowering of floor of, 200
Norway, submergence of, 190
Nova Scotia, Appalachians in, 240; mountains of, compared with those of Britain and Brittany, 284, 285; old red sandstone of, 285

Ocean, earthquake sounds on, 83; islands of, basaltic, 97, 98, 121; absence of continental rocks in, 98, 99; density of rocks beneath, 99; spheroidal form of sea-level, 99; distribution of densities beneath, 101; no borings made under deep, 114; rate of temperature increase under, 114; depth and volume of, 170; changes in level of, in early geological time, 171; the 20-foot shift in level of, 174–179; ice-caps cause of lowering of level of, 179, 180; rise in level of, 184–186; erosion of rocks by, 251; infall of earth's crust caused by weight of, 266, 267; development of basins, 278; basins of, products of continental migration, 291; separation of, from land, 305–312; origin of a single, primitive, 310
Oceanography, importance of study of, 44
Ofu Islands, 20-foot emergence of, 176
Oklahoma, earthquake shocks in, 19; the Appalachians in, 240
"Old Faithful," at Kilauea, 153
Oldham, 88
Ontario, Lake, 201
Orange River Canyon, 93, 94
Oregon, earthquake shocks in, 19; fault cliffs in, 74; basaltic plateau in, 134
Orizaba volcano, 318
Ottawa valley, 201
Ouachitan geosyncline, 203
Overthrusting, in mountain-building, 222 *ff.*; in Scotland, 231; of European Alps, 232–235
Owens Lake, effect of 1872 shock on, 62
Owens Valley, earthquake of 1872 in, 33, 43, 62, 65; quake in, due to faulting, 62, 65; shock of 1917 in, 63

Pacific Ocean, seismic belt around, 6; contour lines of bottom of, 9, 10; the Kermadec Deep in, 10; the Tonga Deep in, 10; epicenters in, 18, 80; a primitive feature of the globe, 90, 265, 278, 291; volcanic islands of, 98, 143; islands of, basaltic, 98, 121; changes in level of, 175–177; system of mountains framing basin of, 218–220; type of coast-line of, 280, 283, 284, 317; origin of, 310; weakening of crust along 25,000-mile shore of primitive, 316; continental sliding toward primitive, 316; origin of mountains along shores of, 316; contrast of type of coast-line of, with Atlantic type, 317; volcanic "Circle of Fire" around, 318

Paleolithic Period, changes of sea-level in, 186
Paleozoic Period, geosynclines of, 203; glacial deposits of, 286; Connecticut in, 294, 295; single, primitive continent at opening of, 311; duration of, 314, 315
Pamirs, energy of landslide in the, 23, 24
Paris, luck of locality of, 6
Particles, accelerations of, in earthquakes, 25; illustration of motion of rock, 84, 85
Patagonia, ice-cap on, 201
Pavement, flexure of, by seismic waves, 28, 29, 65; glacially striated, 286
Peking, 6
Pelée, Mont, 318
Pennsylvania, earthquake shocks in, 19; erosion in, 228; coal-beds of, 285
Persia, readjustment of rocks of, 318
Peru, seismicity of, 11; sea waves of earthquakes in, 41
Philippine Islands, Mayon volcano in, 130; emerged tops of mountain chains, 237
Phreatic caldera, the, of Bandai-San, 158
Physics, importance of study of, 44
Pine Gulch Creek, fault scarps near, 50–53
Pisa, Leaning Tower of, 13
Planets, tidal-disruption theory of origin of, 300–303
Plant, Matthias, earthquake recorded by, 15
Plateaus, supported by flotation, 102; lava, 130–135; erosion of, 139–141
Plato, his Lost Atlantis, 279
Pleasant Valley, Nevada, fault scarp in, 63, 65
Poincaré, Henri, his hypothesis of the moon's origin, 307, 308
Point Arena, 50, 53
Point Reyes Station, California, 58
Ponds, formed by earthquakes, 40, 57
Popocatepetl volcano, 318
Population, density of, and seismic damage, 18
Porto Rico, sea waves of 1918 shock in, 41
Portugal, landslides of 1755 quake in, 33
Pre-Cambrian rocks, 247
Precessional constant, the, 104
Pre-geological eras, 314
Pre-Paleozoic eras, duration of, 314, 315
Pressure, at bottom of earth's crust, 12, 135; effect of, on densities of earth's interior, 104–106, 126; hydrostatic, 115; at base of deep fissures, 124, 135; great internal, and substratum rigidity, 128; results of horizontal, 222 *ff.*, 249, 251, 260 *ff.*
Pretoria, South Africa, sandstone ridge near, 256
Prickett's Creek, West Virginia, bore-hole at, 112, 113
Proteus, 292
Psychology, importance of study of, 44
Pulkovo, Russia, vibrations felt at, 24; seismogram of earthquake at, 87
Punjab, the Geosyncline of, 289
Pyrenees, the, seismicity of, 6; axial trend of, 214; partly submarine, 214; cause of height of, 237

Quartz, crystallized silica, 106
Quartzite, ripple-marks on, 204

Radioactivity, of granitic and basaltic rock, 101, 114; duration of geological eras computed from mineral, 315
Rain-water, volcanic explosion due to superheating of ancient, 158
Ravenna, outside seismic zone, 13
Readjustments of earth's crust, 317–320
Recording of earthquakes, 2, 3; Japanese, 13; with seismograph, 13, 14, 80, 86, 87, 123
Reggio, Italy, earthquake in, 13
Reid, Professor H. F., 58; energy calculation of, 23
Resonance, effect of principal of, 308
Rhyolite lava, 132
Rigidity, of earth's crust, 47, 317; of substratum, 128
Rivers, changes in drainage of, 40; sediments carried by, 203; cutting of valleys by, 276
Riviera, seismic casualties in, 3
Rivieran Alps, 214
Road, offset of, in California quake, 58
Rock-crystal, 106
Rocks, rupture and displacement of, 21, 22; earthquakes attributed to fall of, 46, 74; refraction of wave paths at surface of, 83; illustration of motion of individual particles of, 84, 85; three principal classes of, in earth's crust, 91, 94–97; means of determining nature of underground, 93, 94; density of underground, 94; the igneous, 94–97; crystallizing of igneous, 95; the sedimentary, 96; the metamorphic, 96, 97; of deep-sea islands, 97, 98; absence of continental, in ocean crust, 98, 99; isostasy or balance of, 99; density of suboceanic, 99; densities of, in earth's crust, 100, 101; basaltic, under ocean and continents, 100; character of, in mountain ranges, 102; melting temperature of, 111; formation of stratified, 114, 221; production of flow in crystalline, 115; density of visible, 126; origin of igneous, 129; trachyte, 166; surface-loading due to erosion of, 202 *ff.*; flexing of stratified, into arch, 221; folds and thrusts of, in mountain-building, 222–235; experiments imitating folds and thrusts of, 224–226; the shield, 242–245; the Basement Complex, 245–248; pre-Cambrian, 247; erosion of, by sea waves, 251; centripetal dips of strata, 251–256; theories concerning horizontal compression of, 260 *ff.*; matching of, on two sides

of Atlantic Ocean, 284–287; glacial till, 286; glacially striated, 287; reading of earth's history from, 292–299; mountain structures buried under, 292–299; theory of concentration of light granitic, in one hemisphere, 305 *ff.*; intense crumpling of Basement Complex, 311; ages of, determined through fossils, 314
Rocky Mountains, geosyncline occupying site of, 203; persistence of geosyncline of, 208; overthrusting of, 231; cause of height of, 237; continental migration theory of formation of, 260
Rome, luck of locality of, 13
Roof of the World, the, 320
Roof tiles, use of, in Tokyo, 29
Rose atoll, 20-foot emergence of, 176
Ross Mountain, displacement of, 75
Rossi-Forel scale of intensities, 21, 25, 62
Rotation, earth's ellipticity partly due to, 103; diminishing rate of earth's, 265, 273, 274
Ruggedness of mountains, 238, 239
Russia, in Glacial Period, 189; the Hercynian chain in, 240
Russo-Scandinavian Shield, 242, 264, 274

Sagami Bay, Japan, 14; deleveling of sea bottom of, 70–73, 76; soundings of bottom of, 71, 72
Saint Croix, Island of, 11
Saint Helena Island, basalt flows composing, 120, 121; sand dikes in, 140; monolithic volcanic neck on, 159; trachytic dome in, 166; 20-foot emergence of, 177
Saint-Pierre, 318
Saint Sophia, architecture of, 30
Saint Stephens, New Brunswick, shock at, 16
Saint Thomas Island, 11
Samoa, volcanic islands of, 10; basaltic composition of, 121; trachytic dome in, 166; 20-foot emergence of, 175, 176
San Andreas Fault, 50 *ff.*
San Andreas Lake, water pipes near, 31
San Andreas Rift Valley, pond formed in, by earthquake, 39; aqueduct in, 42, 43; faulting in, 50–61; extent of, 54; displacements parallel to, 58, 74, 75
San Domingo, subsidence of 1751 quake in, 69
San Francisco, collapse of water-supply system of, 1, 29, 41–43; weak foundation of, 18; earthquake of 1906 in, 20, 28, 29, 65; seismic faults in vicinity of, 49 *ff.*; 1868 earthquake in, 62
San Jacinto Fault, 74
Sand-blows, 35
Sand dikes, 35–39
Sandstone, dikes of, 37, 39; ripple-marks on, 204; upturned beds of, 221; quartzitic ridges of, in the Transvaal, 256, 257; old red, of England and Nova Scotia, 285; of Connecticut Valley, 297
Santorin, 319
Sarez, energy of landslides at, 24
Sayles, Robert W., 150
Scandinavia, contemporary warping of, 187–201; in Glacial Period, 188–191, 199; size of last ice-cap of, 190; Caledonian mountain system in, 241; shield rocks of, 242–245
Scarps, fault. *See* Fault scarps
Science, and the earthquake problem, 44
Scilla, earthquake in, 13
Scotland, sedimentary rock in sea cliffs in, 96; banded gneiss in, 97; basaltic lava flows of, 134, 316; ancient volcanic cone near North Berwick in, 157; rock benches and sea caves in Argyllshire, 195–199; geosynclinal strata in, 221; overthrust-planes of, 231; Caledonian mountain system in, 241; plain of marine erosion in, 252; rocks of Highlands of, and Labrador rocks, 285
Sea bottom, changes in depths of, 70–73; the two surveys of Sagami Bay, 71
Sea caves, indicating sea-level shift, 175–178, 195
Sea cliffs, sedimentary rocks in, 96; of basaltic lava, 120; exposing ancient mountain structure, 246, 292, 293
Sea-coast, uplifting of, 66–68, 72; subsidence of, 68, 69
Sea-level, an ideal spheroid of rotation, 99; the ellipticity of the earth and, 103; changes in, in early geological time, 171; the 20-foot shift of, 174–179; causes of lowering of, 179 *ff.*, 209; rise in, 184–186; crustal uplift measured by change in, since Glacial Period, 193 *ff.*; mountain ranges below, 214–219, 237, 240
Sea waves, seismic, 40; list of famous, 41; in Krakatoa explosion, 46
Sedimentary rocks, 96
Sedimentation, mountains formed by prolonged, 220, 226, 239, 242; Basement Complex beneath, 245–248; infall of earth's crust caused by weight of, 266; during Appalachian revolution in Connecticut Valley, 297
Seismicity, two belts of, 6–14, 318; and mountainous zones, 9, 10
Seismograms, the making of, 86–88
Seismograph, Japanese earthquakes recorded by, 13; average number of shocks registered by, 14; location of epicenters by, 80; principle of, 86–87; "discontinuity" recorded by, 123
Seismological Institute of Japan, forecast of director of, 1
Seismology, a new science, 4; its practical bearing on human welfare, 5, 44; knowl-

edge of earth's interior through, 5, 82; books on, 321–326
Sekiya, Professor, model of earthquake motion by, 24
Shasta County, California, sandstone dikes in, 37
Shells, earth's interior formed of successive, 104, 109; composition, depth, and density of, 107–109; silicates of, 107, 108, 304; compressibility of, 212
Shield rocks, 242–245, 249, 250, 264, 274
Shocks, earthquake, fore and after, 76–78
Siberian Shield, 242, 245, 264, 274
Sicily, sinking of coast of, 68
Sieberg, A., his "Erdbebenkunde," 321
Sierra Nevada, eroded fault-blocks of, 259
Silica, compounds of, 106
Silicates, in meteorites, 106, 107; of earth shells, 107, 108, 304
Sills, formation of magma, 160
Silurian Period, 207
Sindree, fort of, 64
Sloop Harbor, Labrador, boulder beach near, 194
Snake River, Idaho, basaltic canyon of, 121
Snowslides, 34
Solar system, tidal-disruption theory of origin of, 104, 300
Sonora, Mexico, area shaken by 1887 quake in, 22; size of fault in, 63, 65
Soufrière, 318
Sound, earthquake, 82 *ff.*; condensational or longitudinal waves of, 83, 84; transverse or torsional, 85; isacoustic lines, 83
South Africa, granitic basement of, 94, 254; bore-hole in, 113; lava floods in, 120, 316; lava flow plateau in, 130; east-west trend of mountains of, 241, 249, 264; crustal-flexure and mountain-making in, 252–257, 316; sandstone ridges in the Transvaal, 256; geosynclines of mountain system of, 264; glacial till of, 285–287; floor of moving glacier in, 287
South America, regional uplifts in, 68; east-west trend of mountains of, 249; supposed westward sliding of, 278, 316, 317; explanation of missing lands east of, 279; floor of moving glacier in, 287
South Carolina, earthquakes in, 17, 19, 20
South Dakota, seismic shocks in, 19
Spanish Peaks district of Colorado, lava dike in, 140
Speculation, the sign-post of, 291
Spheroid, earth an oblate, 103
Spitzbergen, ice-cap on, 201; Caledonian mountain system in, 241
Springs, seismic effects on, 39, 40
Star, theory of planetary genesis through approach of, to sun, 301–303
Strand-lines, records of, 190
Strata, geosynclinal, 221; rock folds and thrusts in, 222–235; crumpling of, 222; anticlines and synclines of, 227; four modes of deleveling of, 251 *ff.*; centripetal dips of, 251–256
Stratified rocks, formation of, 114, 221; flexed into arch, 221
Strokkr geyser, 40
Stromboli, 319
Substratum, earth's, character of, 92, 100–102, 108, 126, 211; increase of density of, with depth, 101, 277; sinking of blocks of crust into, 110, 269 *ff.*, 277; facts indicating existence of non-crystalline, glassy, 110 *ff.*; density of, contrasted with density of crust, 110 *ff.*, 135; viscosity of, 111, 135, 137, 306, 307; white-hot condition of, 114; mountain-building dependent upon glassy, 115, 116; basaltic character of, 119, 126; lava floods from, 120, 121; escape of, through volcanoes, 124; rigidity of, 124, 126, 128, 135, 137; mobility of, 124–128, 168; contradiction in rigidity and liquidity of, 128; effect of pressure on, 135, 137, 211; cause of fissure-eruptions from, 135 *ff.*; basalt of, the heat-bringer in volcanic action, 167; decrease of rigidity with increase of depth of, 211; slippery character of, 269
Suess, Eduard, his theory of arc forms of high mountains, 287, 288; his "Das Antlitz der Erde," 321
Sumatra, displacements in, 76
Sun, the, theory of earth's origin in, 104, 300–303
Superior, Lake, tilting of district of, 187
Suva Diva atoll, 184
Swabia, Germany, volcanic vents of laccolith in, 163
Swamps, caused by earthquakes, 40
Switzerland, overthrust of Alps of, 235
Synclines, accumulation of sediment in, 203–205; in stratified rock, 226; erosion of, 227

Tamalpais, Mount, displacement of, 75
Tau Islands, 20-foot emergence of, 176
Tauride Mountains, axial trend of, 217
Taylor, Frank B., his theory of the migration of continents, 260–263, 265, 278, 287; his theory of arc forms of high mountains, 287, 288
Tectonic earthquakes, 47 *ff.*, 88
Tejon Pass, California, 53
Temperature, rise in, with increase of depth, 111 *ff.*, 126; measurements of underground, 111–114; thickness of earth's crust deduced from, 119; high, of earth's interior, 128, 134; of volcanic magma, 129, 147; nearly constant, of earth's crust, 266
Tennessee, earthquake shocks in, 19; seismic region in, 20; top of an eroded mountain, 239
Tension, caused by seismic waves, 29; in earth's crust, cause of earthquakes, 116;

accompanying continental sliding, 277, 278; crustal, of primitive continent, 316, 317
Terraces, marine, indicating sea-level shift, 178
Tertiary Period, Connecticut in, 296, 297
Texas, earthquake shocks in, 19; Appalachian structure in, 240
Thermal gradients in European borings, 112; in North American borings, 113; thickness of earth's crust deduced from, 119
Thrusts, rock, in mountain-building, 223–235; experiments imitating, 224–226
Tibet, garland form of mountains of, 237
Tidal-disruption theory of solar system, 104, 300
Tide, attraction of lunar, 300, 301; leaping, of molten earth, 308
Till, glacial, of Carboniferous age, 286
Tokyo, quake of 1923 in, 1, 70–73, 76; weak foundation of, 14, 18; use of roof tiles in, 29
Tonga Deep, 10
Tonga Island, seismicity of, 11
Tonga Plateau, 10
Topography, bedrock, and earthquakes, 21, 22
Torrents, mountain, 319
Trachyte, domes of, 166
Trans-Caucasian springs, rise in temperature of, 40
Transvaal, the, crustal-flexure and mountain-making in, 252–257; sandstone ridges in, 256
Transverse or torsional waves, 85; velocity of, 105
Trees, displacement of, in Japanese quake, 58
Tremors, seismic, first and second preliminary and main, 87, 88
Triangulation stations, displacement of, 75, 76
Triassic Period, Connecticut in, 294, 295
Turkestan, energy of 1911 quake in, 23
Tuscarora Deep, the, 10
Tutuila, basaltic island of, 121; trachytic dome on, 166; 20-foot emergence of, 175

United States, earthquakes in, 14 *ff.*; luck of locality of, 18; number of shocks from 1915 to 1923 in, 19–21; eastern and western, seismically compared, 20, 21; the quake of 1755 in, 21; improbability of seismic disaster in northeastern, 21, 22; thermal gradients in borings in, 113; great basaltic plateau in, 134; submergence of, 264
United States Coast and Geodetic Survey, 75
United States Weather Bureau, 20
University of California, 62
Uplift, seismic regional, 65–68, 72; coastal, 193–202
Ural Mountains, 241
Utah, earthquake shocks in, 19; fault cliffs in, 74, 94; laccolithic mountains of, 251; fault-block mountains of, 259

Valleys, cutting of, by rivers, 221, 276
Valparaiso, seismic casualties in, 3; weak foundation of, 18
Venice, outside danger zone, 13
Vermont, seismic shocks in, 19
Vesuvius, Mount, 156, 319
Vibration, causes of, 45, 46; through fracture of earth's crust, 48, 50; causing earthquake sounds, 82, 83; recording of seismic, 87
Virgin Islands, seismicity of, 11; sea waves of 1867 shock in, 41
Virginia, seismic shocks in, 19
Viscosity, of substratum, 111, 135, 137, 306, 307
Volcanic earthquakes, 23, 46, 88
Volcanic explosions, 46, 153–158
Volcanic islands, of the Pacific, 98
Volcano Observatory, 150
Volcanoes, relation between earthquakes and, 78, 79; contrast of density essential condition for, 110; escape of substratum glass through, 124; due to mobility of substratum, 125; one process common to all, 128; temperature of magma of, 129, 147; fissure eruption, 130, 133–141; Ararat, Basutoland and Mayon, 130; central type of, 130, 141 *ff.*; areal eruption, 131–133; Ascension Island, 131; Yellowstone Park lava plateau, 132; earth's crust not endangered by fissure or central eruption, 138, 139; formation of cones of, 141, 142; central type, due to abyssal fissuring, 141–143; most violent, of modern times, 142; alignment of Pacific, 143; magma chambers of, 144–147; gas-fluxing of, 144–147, 168; reasons for long life of central, 144–147, 168; eruptions of central type confined to points rather than lines, 143–147; persistency of activity of, a heat problem, 147; dormant stage of, 148; reasons for intermittent activity of, 147, 148; cause of final extinction of, 148, 149, 168; the abyssal-injection theory, 149; Halemaumau, 150–156; lava lakes of, 151–155; origin of heat of, 153, 154; explosions of, 153–158; high fluidity of lava flows from, 156; effect of explosions on cones of, 157; erosion of cones of, 159; formation of magma sills, 160; with no alignment of vents, 160–165; laccoliths formed by, 161–165; subordinate and principal, 163; chemical diversity of lavas of, 165–168; instability of cones of, 167, 168; in Connecticut Valley, during Appalachian

revolution, 295–298; principal zones of, 318, 319; of the Mediterranean zone, 318, 319
von Wolff, F., "Der Vulkanismus," by, 321
"Vulkanismus, Der," by F. von Wolff, 321

Warping, of earth's crust, 66 *ff.*, 174 *ff.*, 186 *ff.*, 203 *ff.*; cause of tilting of Baltic and Great Lakes districts, 187 *ff.*; after melting of Scandinavian ice-cap, 190; after melting of Labrador ice-cap, 191–194; of Newfoundland, 193–195; two Mediterranean zones of, 264, 274
Washington State, seismic shocks in, 19; basaltic plateau in, 134; lava dikes in, 141
Water, density of salt and fresh, 98; separation of hemisphere of, from land hemisphere, 305–312; a single hemisphere of, 310
Water pipes, effects of compression and tension on, 29, 31; offset in, caused by faulting, 57
Water-supply systems, breaking down of, by earthquakes, 1, 41–44
Waves, visible seismic surface, in ground, 27–29; seismic sea, 40, 41, 46; paths of seismic, 79, 80; seismic sound, 83–88; condensational or longitudinal sound, 83, 84; transverse or torsional sound, 85; the P, S, and M, 87, 88; refraction and reflection of paths of, 88; velocity of seismic, 105, 109, 122; propagation of transverse, and rigidity of substratum, 128; erosion of rocks by sea, 251
Wegener, Alfred, his theory of migrating continents, 260–263, 278, 287; his map of original continent, 261, 280
Well, effect of Calabrian earthquake on, 25
West Indies, seismicity of, 6, 11; emerged tops of mountain chains, 238; east-west Mediterranean Belt in, 248; formation of mountains of, 284; volcanoes of, 318; readjustment of rocks of, 318
West Virginia, seismic shocks in, 19
Wiechert, his theory of P and S waves, 88
Williams Canyon, Arizona, fissure eruption at, 133, 134
Winnemucca, Nevada, fault scarp near, 49
Wisconsin, seismic shocks in, 19
Wood Gulch, California, fault scarp at, 54
Wyoming, seismic shocks in, 19

Yamasaki, N., 72
Yellowstone National Park, lava plateau of, 132
Yokohama, the earthquake at, 1; destruction of, due to alluvium foundation, 14, 18; deleveling of quake in, 70–73
"Yoldia" sea, extent of, 189
Yosemite, the, shock of 1872 in, 62

551.4 D15

a39001 007038162b

66243

551.4
D15

65-1
66-1
67-1
69-1
71-1
72-1
73-1
74-1